THE FUTURE FLIGHT DECK

It is over ten years since this paper was written on behalf of the Guild of Air Pilots and Air Navigators (GAPAN) and the Royal Aeronautical Society (RAeS). The opportunity is now being taken to review, update and edit it in the light of developments to aircraft and the associated systems; these comments are highlighted in this font. Although technology has given the aviation industry new and improved systems the authors see little to change as the principles within the paper have stood the test of time and incidents to aircraft within the past ten years have proved that there is a need to ensure that aircraft are designed and constructed with these in mind.

The following is a review of the paper published in the RAeS AEROSPACE journal in June 1995:

Human automation

Pilots of modern automated airliners, for example the Airbus A320 and Boeing 757, love the electronic map displays but some don't find the "vertical" navigation displays intuitive. Speed tapes aren't as clear as round dials with needles. They are not the best way of presenting rates; and while some strip scales move down as speed reduces, others move up. Throttles and sticks don't move with autopilot, which limits crew "situation awareness", and FMS (flight management systems) can actually increase workload – for instance when you are given a sudden change of runway.

In fact FMS, which was supposed to reduce workload, makes life easy when there's nothing to do anyway but can actually generate work in a manner unknown when aircraft were simpler.

As for low-tech stuff, some switches are ON or OFF when they are up or down, or is It down and up; manuals in some aircraft are out of reach; and circuit breaker labels are impossible to read.

You will find all this and more - and much that is positive - in The Future Flight Deck, a discussion paper published by the Royal Aeronautical Society's Flight Operations Group and the Guild of Air Pilots and Air Navigators. It makes so many good points that, reading its 20 Aerospace-size pages, you want to underline the whole lot.

Written by a group of airline pilots who, it seems, have had experience of every jetliner from Comet/7O7 to Concorde/747, it is balanced in its brickbats and bouquets for Airbus and Boeing aircraft. This paper is Must Read for anyone who flies or designs airliners, especially the latter.

I reckon there have been 15 serious "automation accidents" in the last seven years – five of them in the last year. Half have been fatal and 13 have involved Airbuses (which of course are more automated). The automation accident rate, in my personal opinion, has become critical and can no longer be attributed to pilot error.

This is a perfectly timed and relevant paper. Its main message is that unless automation is "human centred" it will cause problems ("the latest autopilots include so many modes that the pilot may become confused, especially as some modes change without pilot input"). On the matter of throttle and stick movement, there should always be redundancy built into the channels of transmission of vital information, and thrust levers which move [in auto] "are intuitive and give a tactile feedback". Just because technology is available doesn't mean that it must be used.

The expression "counter intuitive" keeps recurring, and I think will find an influential place in the automation vocabulary.

One of the best bits is a quotation from NASA Ames' Dr Charles Billings: "Simplicity, clarity and intuitiveness should be among the cornerstones of automation design". The best bit of all is: "The question is not whether a function can be automated, but whether it should be."

The paper coincides with, though does not refer to, NASA-supported research by the Massachusetts Institute of Technology into cockpit automation. A team analysed 184 human factors incidents reported confidentially to NASA's Aviation Safety Reporting System (ASRS). The research finds that 75% of these automation incidents were caused by the "vertical" displays and few by the "horizontal" (i.e. maps) which are more intuitive.

The RAeS/GAPAN paper suggests more terrain information on the map displays.' NASA is looking at showing descent profiles – you know, as on the old fashioned Jep or Aerad approach charts, plus where you are and with GPWS data.

Don't be put off by the stodgy looking text and preposition-cluttered sentences ("There are few whose privilege it is to occupy flightdecks of transport aircraft who are not at some time critical of aspects of the design of their place of work'). Short sentences and cartoons, which is what pilots on the Clapham Air-bus like, wouldn't detract from the Royal Aeronautical Society's "learned" image.

A sportier, "human centred" edition would even further enhance a study which, in my opinion, is simply the RAeS at its best. Something you can read while using FMS.

PLB/JBR
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THE FUTURE FLIGHT DECK

A DISCUSSION PAPER
BY
THE FLIGHT OPERATIONS GROUP OF THE ROYAL AERONAUTICAL SOCIETY
AND
THE GUILD OF AIR PILOTS AND AIR NAVIGATORS OF LONDON

There are few whose privilege it is throughout their working lives to occupy flightdecks of transport aircraft who are not at some time critical of aspects of the design of their "place of work". Be it structural or physical layout, personal comfort, access to and ease of operation of controls, presentation of flight and technical information, provision of a clear outside view, quietness in flight; there are moments when one may ponder, "why was it designed, laid out or manufactured this way; could it have been improved, and if so, how?"

Fortuitous timing occurred following the 1992 Guild of Air Pilots and Air Navigators "Spring Technical Presentation" on "The Flight Deck for the Year 2000", with the formation of the Flight Operations Group, the 20th Specialist Group within the Royal Aeronautical Society. The opportunity was taken to consider a similarly titled definitive contribution and a Working Group co-ordinated by Captain Peter Bugge was established and tasked: "Position Paper — Flight Deck Evolution". In the event, a discussion paper emerged, since the primary objective is to promote further debate at this stage. Shortly thereafter GAPAN formed a similarly tasked sub-committee drawing upon the wealth of expertise within the Technical & Air Safety and Education & Training Committees. Headed by Captain John Robinson, it was not long before steps were taken resulting in these two operations co-operating to bring to fruition the joint discussion paper that follows. Captain John Robinson's original paper for the Education and Training Committee of GAPAN pointed out that EFIS displays, far from being entirely helpful, could cause a pilot confusion and often required a substantial training input even when a pilot had flown the same type — but with a different FMS or instrument display.

This paper takes the matter much further, into flightdeck layout, electronic flight instrument system (EFIS) displays, flight management system (FMS) control and display and autopilot and autothrottle control systems. Not by attempting to design them, but by pointing the way that a very diverse and experienced group of pilots believe they should be laid out so that they best serve the needs of the Airline Pilot. The practical knowledge and wide experience of its authors stamp it with an authority that should demand attention from all involved in design and development of systems and displays. The paper deliberately avoids a form of words more appropriate to a research or academic paper, being written by pilots presenting the pilots' point of view — they are after all the end users. Technology has advanced at an amazing pace, and will continue to do so. There is no doubt that, in general, safety has been enhanced as a result. However, if increased safety has been a driving force behind this progress, the paper also points out that safety can be compromised if the "end-users" do not find their new equipment to be "user-friendly". Pilots often face the problem of "unlearning" their last aircraft at every conversion instead of building on what they know and have grown accustomed to. We are convinced that this paper should be read by everyone involved in the design and development of flight deck systems and displays. If they can then accept that there is a need for industry-wide agreement on layout and controls based upon good practice as laid out in this paper, this will be a vital breakthrough and a major contribution to flight safety.

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Chairman, Flight Operations Group,
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The members of the Joint Working Group that produced this paper include:

Captain Peter Bugge, FRAeS, Co-ordinator for The Royal Aeronautical Society, Airline Pilot.
Captain John Robinson, AFC* FRAeS, Co-ordinator for The Guild of Air Pilots and Air Navigators, Flight Operations Director and Chief Pilot.
The late Professor Elwyn Edwards, BA, PhD, CPsychol, FBPsS, FErgS, MRAeS, MRIN, Consultant in Ergonomics.
Alan Foster, MPhil, BSc, MRAeS, Test Pilot, Avro International Aerospace.
The late Keith Dougan, Flight Operations Consultant.
Captain Gerry Fretz, FRAeS, FRMetS, Aviation Consultant.
Captain John Hutchinson, FRAeS, MRIN, Airline Pilot, Aviation Consultant.
Captain John Lee, Military and Airline Pilot.
Captain Ron MacDonald, MRAeS, Airline Pilot, Accident Investigator.
Lt Cdr David Midgely, RNR, former operational and maintenance test helicopter pilot.
Keith Smith, BSc(Eng), DIC, former Superintendent, Blind Landing Experimental Unit.
Captain Barry Whitehead, Airline Pilot.
Captain David Williamson, BSc(Eng), Airline Flight Manager.
Captain Paul Wilson, FRAeS MRIN, Military and Airline Pilot.

In March 2005 Captain Buggé became Master of the Guild and in March 2003 Captain Robinson became Chairman of the Guild's Technical and Air Safety Committee.

CONTENTS

1. THE ROLE OF THE PILOT AND THE DEVELOPMENT OF AUTOMATION IN FUTURE AIRCRAFT

The autonomy of the aircraft operation is discussed, defining the pilot's role and developing guidelines for the introduction of new technology and automation. The design of the flightdeck must fit to the pilot, allowing the use of human-centred automation. The pilot should be involved in the operation to ensure his situational awareness.

2. THE FLIGHTDECK LAYOUT AND WORKING ENVIRONMENT

The flightdeck should be a quiet, well-lit and comfortable place in which to work, with all the controls readily to hand. Realistic provision should be made for the requirements of an everyday operation for both short and long haul operations, with emphasis on the requirements of a two-pilot crew. The location of safety-critical switches and controls, and the importance of feedback are discussed. Communications equipment should be of a high standard to cope with the density of the air traffic environment.

3. INSTRUMENTATION

The advent of cathode ray tubes (CRT) and liquid crystal displays (LCD) has heralded a fundamental change in the concept of instrument design. While considerable benefits have been obtained, it can be argued that development has been uncoordinated, and lacks adequate pilot feedback. Information can perhaps be presented to the best advantage by using modern technology to enhance established methods. Automatic presentation of checklists on screens need careful design to ensure they meet the practical requirements of the pilot.

4. FLIGHT MANAGEMENT SYSTEMS

These are considered in detail, bearing in mind the comments on automation made in Chapter 1. The argument for simpler systems is examined. The features required from FMS to ensure a good inter-face with the pilot are discussed, since without a satisfactory interface the FMS becomes a burden to the pilot.

5. AUTOPILOT AND AUTOTHRUST

Autopilot and autothrust systems have become increasingly powerful in recent years, and include not only more facilities than in the past but also integration with FMS. Their design and operation has become extremely important in determining the success of the pilot-machine interface in the flightdeck. Feedback through the control column or side-stick is necessary, and the system authority must be carefully matched to the aerodynamic characteristics of the airframe and engine.

6. NEW TECHNOLOGY

There are several options for the introduction of new technology, but all those considered should be appropriate to the autonomous aircraft. The management of new technology is as important as the technology itself, and digital databases and knowledge-based systems might take over from current FMS. Head up displays and synthetic vision systems should be considered together as a means of executing a safe approach to any runway. There are a number of additional benefits to be obtained from these systems.

7. CONCORDE'S SUCCESSOR

The second generation of supersonic transport will be very different from Concorde, particularly in the avionic equipment it will have and the congested environment in which it will operate. It will need sensors that will allow unplanned variations to the flight plan, and the ability to operate with only two crewmembers.

8. CONCLUSION

INTRODUCTION

This discussion paper presents the deliberations of a Joint Working Group of the Flight Operations Group of the Royal Aeronautical Society, and the Guild of Air Pilots and Air Navigators. Its purpose is to reflect the views of transport aircraft line pilots on the design of future flightdecks. Concorde's successor, B747 and DC-10 derivatives, updated and developed versions of current transport and general aviation aircraft, military and rotary wing aircraft all offer opportunities for significant improvements in flightdeck design. Although there are inputs to manufacturers from other pilot bodies, there is a clear need for feedback from line pilots, as well as from industry test pilots and operators' technical managers. Most importantly, the views of line pilots must be taken into consideration at the design stage so that pilot/machine interface problems caused by the introduction of new technology are avoided. The examination of problems after they have been introduced is wasteful in human terms, and not very productive because the equipment that is causing the problem may be fundamental to the operation of the aircraft and impossible to alter. There are many codes of practice, and requirements laid down by certificating authorities, and it is not the object of this Paper to be dogmatic or to tell manufacturers and designers how to do their job. Rather, it utilises the wide experience of the pilots and human factors specialists in the Group to suggest lines of thought about the pilots' role in the next generation of aircraft, and how equipment might be better integrated with the pilots' requirements. It will not be enough simply to increase the amount of new technology and automation used in future flightdecks. The human limitations and requirements of the pilot must be the controlling parameters of flightdeck design. It is felt particularly desirable for the pilot voice to be heard through the Royal Aeronautical Society and the Guild of Air Pilots and Air Navigators, since they represent a huge reservoir of experience in all aeronautical disciplines, and manufacturers, designers and certificating authorities are urged to consult and benefit from their knowledge.

Captain Peter Buggé, Co-ordinator for the Flight Operations Group Royal Aeronautical Society.
Captain John Robinson, Co-ordinator for the Guild of Air Pilots and Air Navigators.

Winter 1995

1. THE ROLE OF THE PILOT AND THE DEVELOPMENT OF AUTOMATION IN FUTURE AIRCRAFT

The autonomous operation

1-1 A proper discussion of the evolution of the flightdeck first requires adequate definition of the pilot's role, so that the problems and needs of the interface between pilot and aircraft can be recognised. From this, in turn, will follow the satisfactory design of the flightdeck itself, its environment, and all its associated automation, instrumentation and equipment.

1-2 The fundamental question of the pilot's role in the future flightdeck concerns the degree of autonomy of the aircraft's operation; will it be controlled from the ground and depend on ground based facilities, or be self contained to the extent that it is controlled by, and under the authority of the pilot? While there is little to prevent control of the aircraft from the ground being the philosophy on which the future development of the flightdeck is based, this is only practical in a relatively restricted operation involving parts of the world where there is already a high level of technical support of, and demand for, aircraft operations.

Some of the problems of this approach to the development of aircraft operations are well demonstrated by the number of accidents that occur to very sophisticated aircraft operating in parts of the world where ground aids to navigation are few, and communications poor. The pilots may have been provided with a flight deck ill-suited to the task they have to perform when away from the major airports, and that part of the reason is that the flightdeck and its equipment have not been designed to be completely under the control of the pilot, and to assist him in a self-contained operation. Aircraft designers might bear in mind that a very high proportion of commercial flights will continue for many years to be into unsophisticated airports, where much of the advanced technology available both in the aircraft and on the ground is presently unusable, and that many helicopter operations will be in support of oil rigs and exploration in remote parts of the world.

1-3 It is worth noting that where manufacturers do provide the means for the pilot to control the aircraft operation without immediate dependence on ground facilities, certifying authorities may not approve the use of the equipment because of a lack of long-term up-dating facilities such as DME or VOR. It is appreciated that the major reason for these restrictions is the inaccuracy of the FMS database because of human error, inaccurate original data, or a failure to adhere to agreed timescales, such as Arinc 28 day, for the introduction of changes. However, this does not alter the fact that the pilot is expected to operate in a way that is incompatible with the design of the equipment he is using. Thus, the pilot finds himself in the situation of having the ability to conduct an approach using the FMS with far lower workload than using an NDB or VOR, yet forbidden to do so even in areas with good ground aid coverage which allows errors such as map shift to be monitored. Not only is he prevented from using the equipment in the way it is designed to be used, he is given the added disadvantage of having to operate in a more awkward way during a critical stage of flight. Similar constraints have been placed on helicopter operations in the North Sea, and it is hoped that the development of a specific Helicopter Approach Aid will receive full support from certificating authorities, and consultation with the pilots who will use it.

Close cooperation between the manufacturers and the certificating authorities is ever more important, and they must not lose sight of the practical aspects which would be of benefit to the pilots and result in a safer operation. The autonomous aircraft may require new rules for operations at under-developed airports.

2005 Comment. The increasing acceptance of global navigation satellite systems (GNSS) for navigation purposes will enable inputs to be made to the FMS so that this system can be used as an approved approach aid.

1-4 Continuing the discussion of the autonomy of the pilot's role, experience shows clearly that aircraft operation is one of continually modifying and updating a course of action, often in the light of weather changes or equipment failures. Passenger comfort, aircraft performance, and commercial considerations will all affect the operation. In many cases the correct, or best, decision can only be made as the result of the pilot's experience of past situations, and in extreme cases of multiple or catastrophic failure only the skill of the pilot, using the flexibility and inventiveness of the human brain, can prevent an accident. This constant assessment and modification of a situation requires that the pilot has all the information needed available to him at all times, since ultimately the responsibility for the safe conduct of the flight will always rest with him.

1-5 The pilot's role, then, must always be a central one, monitoring, deciding, controlling and, in emergency, overriding. The flightdeck represents the only central location to which information can flow, where it can be assessed and used as appropriate to modify actions and form decisions. The pilot's role must be recognised as the central theme in the design of the future flightdeck, since it determines the equipment installed as well as its design, and the ground based functions of navigation, control and communication should, where possible, be aligned with this theme.

Pilot awareness and involvement

1-6 To permit the pilot a central role in the flightdeck, it follows that he must be aware of the situation in which the aircraft is operating at all stages of flight. He must know the status of systems and engines, and whether performance and navigational requirements are being met. The basic flight instruments must show continuously the attitude, speed, height and heading of the aircraft, together with such other parameters as may be needed at particular phases of flight.

1-7 To maintain awareness when work loads are low and to avoid the stress of high workloads when problems arise, is a desirable state of affairs that is seldom encountered in current aircraft, yet it is a fundamental part of the satisfactory interface between the pilot and the aircraft equipment and instrumentation, and one which modern technology should allow designers to achieve. Often the cruise phase of flight is monotonous, with a low level of activity for the pilot when all is going well, yet it is highly automated. Navigation is done automatically, little systems switching is required, and autopilot and autothrust fly the aircraft. Following failures, though, autopilot and autothrust may not be available, and complex systems degrade in many different ways, adding to a high workload in a manner that did not happen when aircraft were simpler. Providing emergency checklists on screens in aircraft with "glass cockpits" may not help the situation, either because of screen failure or because of confusion and difficulty arising from the amount of information to be displayed and the order in which it is displayed. Even when there is no unserviceability, some phases of flight can generate high workloads at undesirable times, for example, when executing a non-precision approach, or an instrument landing system (ILS) approach followed by a break-off and visual circuit, when the advanced technology incorporated in the aircraft may not be available to the pilot in an easily used form, and may need special programming. Even such normal activities as programming the FMS following a re-routing require a large crew input. It can be seen that the availability of modern technology may obscure what is actually desirable or necessary.

The argument for simplicity

1-8 If this philosophy is taken one step further, an outline starts to emerge on which the design of future flight decks can be based. To keep a suitable level of arousal and awareness in normal en-route operations, some straightforward tasks can be left to the pilot, and do not need to be automated. The main requirements are good communications equipment, especially for long-range operations, and accurate basic equipment with which to navigate. FMS's that have a complex interface with the pilot are unnecessary when all goes well, and tend to add to the workload when problems occur. Simple but accurate performance data computers, used with an area navigation system, offer a simple, practical and cost effective combination that helps the pilot under all conditions. Much adverse comment has been made about the increase in workload caused by complex equipment that requires extra skills and knowledge to operate or interpret on occasions when the simplest form of instrumentation is all that is required.

New techniques and piloting procedures that are unnatural or counter intuitive in relation to past experience, or which reduce a pilot's situational awareness, could in the future, become part of a chain of accident causes. This suggests that a simpler flightdeck, based on proven equipment and instrumentation that is natural and instinctive to use, could have advantages. The point has already been made (Ref. 1) that the question is not whether a function can be automated, but whether it should be, due to the various human factors questions that are raised. The assumption that automation can eliminate or reduce human error may be false. There are failures in the interaction of humans with automation, and in automation itself. Some information should always be displayed in basic form, making monitoring easier and simplifying emergency operating procedures. Maximum use should be made of controls feedback and tactile cues, and the pilot should be actively involved at critical stages of flight. No matter how sophisticated the instrumentation and equipment becomes, the basic parameters should always be available, particularly for the flight instruments, presented centrally in a clear, unambiguous way. The more complex information and automation should fit around this basic display, which should not be relegated to "standby instrument" status.

1-9 The argument for simplicity in the flight deck is furthered by the problems already being experienced in managing and presenting the huge amount of data currently available in new aircraft, particularly in the military sector. The potential difficulties in adding data-links such as Aircraft Communication Addressing and Reporting System (ACARS), automatic input to the FMS of air traffic control (ATC) instructions, and electronic library systems, in a form that is easy to use and manage, are immense. Automatic input into the aircraft systems from outside sources would take the pilot out of the loop, breaking down the mental model that every pilot relies on. Increased adoption by the commercial sector of capabilities thus far the domain of the military operator, (infra-red sensors, synthetic vision, onboard databases, voice command systems), require an increasing human engineering effort to ensure that the crews are not distracted by a system, or preoccupied with information extraction at an inappropriate moment. Man-machine integration driven mistakes have been made in the past with attendant penalties in safety and economy. It is also possible to envisage a situation arising where the sheer volume of information available, and the confusion it causes, is a major contributor to an accident.

The integration of new technology

1-10 New technology requires a reassessment of training methods, and recognition that crews are not being taught enough to fully understand the aircraft systems. A higher level of teaching is required because aircraft systems have insufficient intuitive feedback to allow crews to understand what the systems are doing and how they are interacting. The training must be improved to prevent the laying of a foundation on which "pilot error" can be built. Appreciation of the difficulties line pilots may experience in learning and using new technology may be masked by the high level of technical knowledge required of pilot managers so that they may communicate effectively with manufacturers. These pilots are, as a result, no longer representative line pilots, and manufacturers may not get an accurate feedback of the line pilots' views on equipment in service. For the same reason manufacturers' test pilots may not be representative of the average line pilot.

1-11 At a manufacturing level, man-machine interface design philosophy, cognisant of aircrew feedback, must be incorporated at the birth of a new project in much the same manner as Quality Assurance (QA). Attempts to retrospectively design the cockpit environment after the engineering and economic analyses are complete produce unsatisfactory results. It is questionable whether the new technology available in today's aircraft is there to help the pilot, or for some other reason. The development of new equipment to enhance ATC, the commercial capability of the operator, or the efficiency of the aircraft systems is only acceptable if it is designed and installed with the idea firmly established that it must fit to the pilot, not the other way round. There are many examples of technology benefiting the pilot, giving more accurate instruments, information on systems, weight and centre of gravity (CG), pictorial navigation displays, and airframe and engine parameters defined on instruments by coloured segments; but there are also examples of computerised switch panels, and displays of systems parameters that are no more than gimmicks, fitted to aircraft that are thus made more difficult to operate than their simpler predecessors. It should also be clearly understood that, while improvements in automation technology can help humans accomplish new and more difficult tasks, they should not be used to

increase system throughput beyond the limits of human capability to operate manually in the event of automation failures.
1-12 Any new concept should be thoroughly tested before production, not just for mechanical reliability but also for its intended function and application, using all available means. Much research has been done, for example, on instrument design (Ref. 2), yet strip instrument displays, which can be shown to be unsuitable in some applications, are in wide-spread use because it is easier to incorporate them into glass cockpit displays than analogue-style instruments. The information presented by strip instruments is often unclear and ambiguous, and the pilot finds himself using an instrument that is not as suitable to the task as it could be.

Human-centred automation
1-13 Technology is bringing new problems to the flightdeck, in some cases contributing to accidents and incidents. Many pilots see much of this new technology as superfluous particularly where it impinges on airmanship and decision-making. The calculation of approach speed by the FMS is an example; only the pilot can know and allow for all the factors affecting the selection of the final approach speed, and to encourage pilots to rely on electronics instead is surely a shortsighted policy. Automation associated with pictorial navigation displays, and the principles of FMS for example, are generally welcomed, but only if they are designed to be easy to use and do not generate more problems than they solve. The B757 FMS is acceptable, but because the pilot-machine interface is so poor, FMS fitted on some other aircraft is not.
It seems that there is widespread misunderstanding of the meaning of automation as applied on the flightdeck. There is the sort that we have had for a long time, like autopilots and autothrust, which help the pilot but do not generally make decisions for him. The pilot makes use of them to keep his workload under control, but even with the autopilot engaged for example, the pilot is still "flying" the aircraft because he is still making the decisions and the controlling inputs. This sort of automation is now getting unnecessarily complicated, and problems are arising where none existed before. Then there is automation that operates and controls the systems and these are generally very good, requiring little pilot input although there can be difficulties keeping the pilot aware in abnormal situations. Aircraft that use fly-by-wire have another level of automation, the flight control computers that provide protections and information. In normal flight, and during abnormal flight when operating within standard operating procedures, the pilot will not be conscious of the existence of this type of automation as long as control inputs remain conventional.
Lastly, and most important, is the type of automation that makes decisions for the pilot, typically the FMS. It can generate work in times of high workload, and make life easy when there's nothing to do anyway; it may require a pilot input just to keep warnings and messages cleared even when they have nothing to do with the stage of flight at the time. When operating to runways without an ILS, (and there are many of them, even in Europe), the FMS may still have to be programmed even though it can't be used because of database errors that generate map-shift. It can alter the autopilot and autothrust modes without pilot input depending upon selections such as the engagement or otherwise of the flight director.
1-14 To some pilots an increase in automation means less hand flying, and they are against it, they are thinking only of the increase in the use of the autopilot that is necessary in today's ATC environment. To others it means better systems control, and they are in favour. Yet others might think it means that electronics make the decisions that affect the safety of the aircraft for which they are legally and morally responsible, and they are against that.
The essence of this discussion is that the success of any automation is dependent on simplicity and the quality of the pilot-machine interface, and this chapter can be summarised by noting some guidelines for human-centred automation set out by Charles E. Billings (Ref. 3):
"The pilot must be in command. He has the ultimate responsibility for the operation. Automation is not infallible, and human responsibilities include detecting failures, and continuing the operation safely until the automated systems can resume their normal functions.

"To command effectively, the pilot must be involved. The pilot's involvement must be consistent with his or her command responsibilities.
"To be involved, the pilot must be informed. Certain information must be present if the pilot is to be involved and able to assume control in the event of automation failures.
"Automated systems must be predictable. They must perform their tasks as pilots expect them to, in order that performance failures are more obvious.
"Functions should be automated only if there is good reason for doing so. Would automating a new function improve pilot capabilities or awareness? Would not doing so improve the pilot's involvement, awareness, or ability to remain in command? Both these questions should be asked before introducing a new element of automation to the cockpit.
"Automation should be designed to be simple to train, to learn, and to operate. Simplicity, clarity and intuitiveness should be among the cornerstones of automation design, to make it a better and more effective tool.
"Keep the pilots involved by requiring them to do meaningful and relevant tasks. Keeping pilots involved may require less automation rather than more, but is critical to their ability to remain in command of an operation".
1-15 Perhaps we could all humbly learn something from our fellow creatures as, watching several thousand birds indulging in all sorts of activities near a cliff face it is difficult not to be amazed by the fact that, despite their very close proximity in three dimensions, they don't collide. It is also fascinating that they navigate vast distances, in both small and very large numbers.
All this is managed without masses of ground equipment, and thousands of people, (or should we say birds?), talking to them from the ground; think of the cost saving!
How then is this achieved? The answer is simply that they have superbly designed and monitored on-board systems and sensors giving them the information they need. It seems that, for millions of years, we have in fact had autonomous airborne flying machines.

2. THE FLIGHT DECK LAYOUT AND WORKING ENVIRONMENT

The use of space
2-1 Because the space available in a flightdeck is limited it is most important that care is taken not to waste it. Compare, for example, the space taken by the control column in a B757 with that taken by the side-stick on the A320. While it may have other advantages the conventional control column occupies far more space than the side-stick, getting in the way of the pilot when he is moving into or out of the seat, making it difficult to put paperwork on his lap, and partially obscuring the lower part of the instrument display. Or, consider the amount of space taken by a pedestal panel between the pilots' seats, the rear part of which might be better used for document stowage, perhaps in the form of a pull-out tray, so that both pilots on a conventional two pilot flightdeck would have easy access to references which are in frequent use during flight. On the A320 most manuals are out of reach of either pilot, being located on the floor of the wardrobe space, and on the B767 some are not even located in the flightdeck at all. It seems unlikely that manuals and documents will be displaced by an electronic library for some years yet, not because of hardware or software problems, but because of the difficulties associated with the accuracy, updating, and accessing of a very large amount of data. Certifying authorities and operators will also have to agree compatible systems for record keeping and cross-reference.
2005 Comment. The electronic library is being accepted as an efficient way of keeping the amount of paperwork on the flight deck to a minimum. Navigation and approach charts are being developed for electronic displays and it is essential that they are provided in a logical sequence and access to a ready reference.
2-2 The use of seats that move to the side as well as back to provide access, as on the B757 and A320, make good use of space, and avoid the need for the pilot to climb over the seat to gain access as on the B737. The motive power of electrically operated seats, however, should be limited to avoid injury if a hand or leg gets caught between the seat and surrounding flightdeck trim. Jump seats can be designed, as on the A320, to take up very little space when stowed. At the other extreme, the B737 flight deck is too small to permit use of the jump seat without seriously

intruding on the operating crew's own seating and working space. Where special equipment is going to be fitted for aircraft missions such as helicopter search and rescue, space should be provided for it in the initial design, so that the pilot does not have to be surrounded by equipment specific to his task for which there is no adequate stowage.
2-3 Some thought should be given to the provision of chart holders to hold let down and departure charts, a secure holder or two for coffee mugs, a rubbish bin, and clips or guides to keep headset leads out of the way, simple items that make an enormous difference to the efficiency and comfort of the crew. Fitting sun visors that retract into the side windowsills, where they are kept clean and easily available, can save space. Emergency equipment should be stowed securely in properly designed holders, rather than clipped to bulkheads where it can be knocked by anyone moving past; and circuit breaker panels should be located where their labels can easily be read, but without being angled so that they mask the circuit breakers below as is the case on the B737. They should also be illuminated at night. The current trend to locate circuit breakers away from the flightdeck should be considered carefully in conjunction with the requirements of smoke and fire drills. In larger aircraft, a wardrobe space is always appreciated, especially where security requirements prevent easy access to hold-stowed crew baggage at destination.
2-4 Current aircraft design places FMS and radio selectors where they can either be operated only with one hand, or by one pilot and not the other. FMS design will be discussed in a later chapter, but it is suggested that a better use of space could be made by re-siting the FMS keyboard more centrally to the pilot, perhaps with a "qwerty" keyboard that can be operated with two hands, and with a roller ball or mouse control. It could stow for takeoff and landing in the same way that the A320 tray is stowed under the flight instrument displays, or slide to one side. Radio selection through the FMS keyboard, as is done for navigation aids on the A320, or through touch-screens, would release more space and allow either pilot to select any radio facility. However, changing a series of numbers by rotating knobs is a more instinctive and accurate process than using buttons to select the numbers, so may be preferable for some applications such as selecting communications frequencies. The management of communications and FMS in future aircraft will need to be integrated with the use of knowledge based systems, datalink, and perhaps multipurpose digital databases, which are discussed in Chapter 6.

The working environment
2-5 Modern aircraft should provide as comfortable and efficient a working environment as any office. The smoothness of panel design and the choice of colour scheme cost no more to get right than to get wrong. Compare the A320 and B757 for the two extremes in modern transport aircraft, the former giving an immediate impression of space and light, whereas the dark brown colour scheme and angular panel layout of the B757 can give a depressing effect. Pilots spend long hours seated, and the best efforts of aircraft designers have so far failed to provide the levels of comfort attained by the motor industry in either physical or environmental terms.
2-6 Noise levels from external sources have dropped dramatically in recent years, allowing internal noise levels to become dominant. Coming mainly from air conditioning and equipment cooling, this noise can attain a sufficiently high level to impede communication. It may be associated with poor design of vents and grills, which will also cause draughts that can be difficult to reduce. Even flightdeck door design is significant, that on the A320 allowing cabin crew passenger announcements to be heard in the flightdeck, often at times of high workload when it can be very distracting.
2005 Comment. The requirement to fit high security doors to the entry of the flightdeck has helped solve the extraneous noise problems.
Rotary wing aircraft have levels of noise and vibration which can seriously impair the pilot's ability to operate the aircraft, and which add significantly to fatigue. These aircraft spend most of their working lives in adverse weather relatively close to the surface, so special attention should be given to weatherproofing the aircraft and equipment, and providing reliable heating, ventilation and air-conditioning. In long-range aircraft, the control of humidity and air quality are important.

2-7 Flightdeck and instrument lighting should conform to a few simple rules. Each pilot should have full control of his own lighting, of his instruments and around the seat area. All dimmer controls should dim to zero, and not extinguish the light when it is only partly dimmed. Chart lights that illuminate a space or shelf for writing should shine on the paper, not the back of the writing hand. Many older aircraft had much better lighting than current aircraft, and this is perhaps an area where more discussion should take place between the manufacturers and the line pilots who actually do the night flying. Glass cockpit instrument displays sometimes suffer from inadequate dimming capability, which can be distracting when maximum external vision is required. Ice detector probes, which should always be fitted and visible from both pilot positions, should be lit. Illuminating the leading edges of the wings for ice detection is a poor substitute, since it is almost impossible to tell whether there is ice forming or not due to the angle of the light and the pilot's limited view. A comprehensive ice detection system should be original equipment on all aircraft cleared for flight in icing conditions, correlated with angle of attack sensors to maintain the accuracy of alpha-based warnings and data. Windscreen wipers should be of some practical use, clearing a reasonable area of the screen without leaving patches untouched and able to deal with a large volume of water.
2-8 The pilot's view is usually better on modern aircraft than was the case with the early jets, but there are still significant differences between types. Notwithstanding the increasingly controlled environment in which they work, it is still essential for pilots to have the best possible external field of view, whether operating in closely controlled airspace or into basic landing strips. It is also important to have a guide to the aircraft attitude in the form of a good, strong horizontal cut-off to the top of the glare shield or coaming in front of each pilot; a short horizontal cut-off at the centre of the coaming is of little use. It should always be possible to see at least the wing tips of any aircraft, to assist the pilot when taxying in confined spaces. Development of external cameras should be continued, perhaps showing benefits in proposed very large civil transport (VLCT) operations, although the problems of night vision and pilot interface are recognised.

Controls and switches
2-9 Flying controls should be well harmonised, with asymmetric rudder loads much lighter than those in current aircraft, which seem to reflect a purely traditional idea of the loads associated with an engine failure on take-off. A rudder bias system such as that fitted to the BAe 125, to apply the correct amount of rudder deflection when the aircraft is operating under asymmetric power could be more widely used. While it may be difficult in fly-by-wire aircraft to provide tactile feedback between pilots' flying controls, whether side-stick or traditional column, it is felt desirable that this should be done. The argument for an indication of aircraft pitch trim through stick or column position to be available to the pilot at all times is very strong. There seems to be no practical reason why side-sticks should not be mounted inboard rather than outboard of the pilot if this allows a feedback mechanism between them to be fitted or, because both controls would be easy for the pilots to see, removes the need for it. Linking outboard mounted thrust levers should not be difficult. The helicopter pilot's task would be much easier with controls that offer pure uncoupled movement, a concept that must become a reality with fly-by-wire technology. It seems desirable that there should be a common standard of inceptor for this application, using four or six axes; there is an opportunity to standardise on this fundamental choice, and line pilots should be involved in the decision.
2-10 The operation of all controls and switches should conform to conventional thinking regarding direction of movement and resulting indications. If switches are vulnerable to inadvertent operation that could be dangerous, suitable guards should be provided; roof panel mounted switches are often vulnerable to being struck by a crewmember's head when entering or leaving his seat. Due regard must also be made to the suitability of size, shape and position of each control or switch. For example, the use of a large, wheel-shaped lever for raising and lowering the landing gear may restrict the location of that lever to an inconvenient place on the co-pilot's panel, where the captain has difficulty reaching it. A smaller switch or lever, centrally placed as it was on the Viscount, might be a better arrangement. The appropriate shape could still be incorporated.

Similarly, a large flap lever, which on Boeing aircraft, is placed in line with, and to the right of, the large thrust levers, is difficult for the captain to operate precisely. The alternative of a smaller lever that is centrally placed, as on the A320, is more acceptable. At the other extreme, small buttons used to select power changes on the B757 are set on the co-pilot's side of the centre panel and are difficult for the captain to reach. In turbulence there is a risk of incorrect selection that would be avoided by a more central location or larger buttons. Manufacturers should be aware that many airlines expect and encourage their crews to operate as both handling and non-handling pilot, and these frequently-used controls should be equally accessible from either seat, which would not only make normal operation easier but control of the aircraft following incapacitation of a crew member safer. It may be advantageous to operate some control functions, in addition to autopilot cut-out and radio transmission, from the control column or side stick, as is done in military aircraft. In rotary wing aircraft, use of a conventional FMS keyboard is made difficult by the need to keep both hands on the aircraft controls at certain stages of flight, and an alternative means of accessing the FMS is needed. Perhaps the FMS display could have a menu and cursor, selected and activated by a rocker switch and press button. Voice activation might also be successful in this situation. Placing the FMS keyboard at the optimum angle and position in relation to the pilot could reduce the problem.

Roof panels

2-11 The use of roof panels for controls and indicators that are used regularly causes a number of problems. It is very difficult to see panels that are close to one's face, or to read the labels, especially at night, and if the panels are all laid out in a uniform style, as on many aircraft, it is easy to make a wrong selection. Some controls may be found almost out of reach above the pilot's head, and this is obviously unacceptable. It is undesirable to place safety-critical controls, such as fuel control switches or fire handles, in locations where a pilot has to turn his head significantly to see them, or reach above his head to operate them. Something like an evacuation alarm, that is hardly ever going to be used but which is extremely important, should not be located out of sight above and behind the captain's head, as it is on the A320.

2-12 Roof panels are the usual place to find switches and knobs of the same design, controlling different functions yet adjacent to one another. The engine anti-ice selectors and hydraulic systems switches on the B737 are a classic case. The use of switch lights can present a similar confusion, one small black square looking much like another. Perhaps there is a case for larger labels, or the substitution of touch screens for the systems indicators and switches usually found on the roof panels. Certainly, the use of screen displays for systems information, as used on the A320, is an excellent use of modern technology, and reduces the amount of information that needs to be displayed on the roof panels. Further development might enable the complete removal of systems controls from the roof panels.

2-13 Engine fire indicators and extinguisher handles come in all shapes, sizes and positions. The instinctive action to operate an extinguisher must be to press a red warning light, but on some aircraft the required action is far from instinctive, and the extinguisher switch is outside the pilots' normal view. Other aircraft have fire handles that can tangle with each other if all are operated together, as in a runway over-run situation. The warning itself is obvious if written in red on the screen in front of the pilot, and an illuminated switch of average size adjacent to the appropriate engine fuel control or thrust lever, which can be pushed to discharge the extinguishant, is probably all that is needed. Sensors for flame, heat and smoke should be chosen with care, so that there is no doubt about the condition that has triggered the warning. New flightdeck displays and electronic systems offer an opportunity for fresh thinking on fire warnings and extinguisher operation in aircraft.

2-14 Among the most used controls on any modern transport aircraft are those on the autopilot, yet many are unsatisfactory. Airspeed, altitude and heading selectors are often the same size and of very similar shape, usually set in a line with uniform spacing between them, and while most selected values are shown by LCD numbers, there are still mechanical types available which can be difficult to set and read. It is time for a radical rethink here, perhaps changing the shape or orientation of the panel as well as the controls. Some controls are safety critical but multifunctional, which is undesirable unless there is very clear feedback. The switches found on many autopilot control panels may be illuminated to indicate operation of the switch, but this is instinctively assumed to indicate engagement of the function controlled by the switch, which may not necessarily be the case.

Communications equipment

2-15 The controls used even more than the autopilot selectors are those on the communications audio selector boxes. They usually comprise uniform rows of buttons whose position may be difficult to observe. Some manufacturers make them down when "on", others up when "on", which is easier both to see and feel. Some boxes make all the buttons level whether "on" or "off", but illuminate the ones that are "on", depriving the pilot of the ability to feel the position of the button, and relying on a level of illumination that may be inadequate. It seems desirable to link a transmit and receive function together, but some boxes do not offer this feature thereby increasing the chances of a mis-selection. Volume control is usually managed by rotating the buttons, which tend to be too small for this to be easily done. It should be possible to incorporate some form of automatic gain control to give a level output to the pilot's headset or speaker regardless of the strength of the received signal, thus minimising the adjustment required to the gain control. A separate side tone volume control would be appreciated, as would pilot control of signal-to-noise ratio (squelch), allowing the pilot to set the balance of the incoming signals to his taste. Associated with the audio selector boxes are the transmit switches which should be convenient to use with either hand. With a conventional control wheel, this means that one switch should be on the outer half, and one somewhere on the pedestal. In today's air traffic environment simultaneous radio transmissions are a significant problem, yet the means exist to solve it. Development and installation of such equipment would be widely appreciated by pilots and controllers alike. Cordless headsets might be considered on safety grounds as well as those of convenience and comfort. They would allow communication to be maintained when a crewmember is moving about the aircraft, perhaps to determine the cause of a problem away from the flightdeck, and would be of assistance during an emergency evacuation.

2-16 The advent of modern technology gives designers an opportunity to rethink many of the traditional ideas on flightdeck layout and the pilot's working environment. Many developments are of undoubted benefit, perhaps the best examples being the pictorial navigation and systems displays, and automatic systems operation. However, the interfaces with these displays, and the layout and environment of the flight deck, have not developed at the same rate, and are still based on traditional ideas. Large handles and levers would seem out of place today, though some of the tiny selectors on radio control panels are perhaps going too far the other way. There is considerable research and practical experience on human factors and ergonomics available outside and inside aviation to help manufacturers provide flight decks that are safe, comfortable, and easy to work in. They will be as welcome to the line pilot as any new instrument or control system.

3. INSTRUMENTATION

The development of instrument displays

3-1 Instrument flying was developed after the First World War, and mechanical and electromechanical instruments evolved into the 1970s with increasing reliability and readability. Throughout the 50 years or so of this evolution to a very high technical standard, the same basic presentation was maintained, such complex instruments as flight directors, ILS presentations, fast-slow indicators and high speed limit indicators all being accommodated without requiring the pilot to learn new methods of instrument flying. A worldwide standard was established that has stood the test of time

3-2 The introduction of glass cockpit displays has made possible alternative presentations, and over a relatively short time large changes to an established pattern of instrumentation have required pilots to adapt their instrument flying techniques to cope with the new instruments that have appeared. Some of these changes, such as pictorial navigation and systems displays, are of undoubted benefit to pilots, and enhance the safe operation of aircraft. Others, however, mainly associated with the flight instruments, might be considered a backward step, introducing instruments that are difficult to interpret under some circumstances and requiring special techniques to be learned by the user. While it is accepted that manufacturers may be constrained by commercial factors and codes of practice, it is evident that a deeper understanding of the way pilots use instruments could help to make future designs more acceptable.

Basic requirements

3-3 Flight instruments are required to substitute for the visual cues of the outside world and to inform the pilot what the aircraft is doing; they are required to display the attitude and performance of an aircraft. Additional information can be given to guide an aircraft along a specific flightpath. The displays to achieve these objectives must be simple, easy to operate, and capable of interpretation with the minimum of thought process especially in rapidly changing situations. They should appear natural and intuitive so that in high stress situations the pilot can rely on basic interpretative skills, increasing the mental capacity available to deal with operational problems. There should be simple ways of dealing with display unserviceability, and emergency, standby or alternative instruments should be easy to interpret and aligned as closely as possible to the scan of the normal instruments. They should also be of the same style and presentation as the main instruments, bearing in mind that they could be used in abnormal conditions and emergency situations, when an unfamiliar design could cause a further increase in a workload that is already high. Indeed, the safety of passengers and crew could well depend on the ease with which such instruments can be used. Instruments for emergency use should be available to either pilot, driven by independent architecture from independent sources. Single instruments that are a combination of two or more separate indicators, like the combined airspeed and altimeter that is quite widely fitted, may be particularly difficult to use, and should be considered by the certificating authority in relation to the situations in which they are likely to be used in real life. That they are found to be satisfactory by a test pilot in the simulator does not mean they are suitable to fit in an aircraft.

3-4 The problems evident in modern instrument systems fall into two general categories:

a. The introduction of a single display (the Primary Flying Display or PFD) for the primary flight instruments has led to a cluttered picture from which it may be difficult to extract the required information. The limitations on space have led to the widespread use of strip instruments some of which, such as the vertical speed indicator (VSI) on the A320, are arguably too small to adequately fulfil their function. Many pilots find strip instruments lack the instinctive presentation of information given by an analogue display, particularly when there may be different movements to give the same information — on one display the speed scale may move up to increase the value shown, on another it may move down. Perhaps an industry standard would be appropriate here. The PFD has become a separate system of its own, moving away from the simple philosophy of the "basic T", and in so doing has given rise to new problems.

b. The modern screen presentations may be associated with the operation of automation and systems that make the pilot remote from the data or information that he is trying to use. The integration of the FMS into many of the aircraft systems, and the pictorial presentation of performance data on screens are two examples. This requires special pilot training, often to enable him to deal with situations that rarely occur. Programming requirements may introduce errors that would not have been possible with older instrumentation; and the use of advanced technology in a basic environment, such as a non-precision approach, may introduce high workloads and operating difficulties (para 1-3).

The primary flight instruments

3-5 Instrument flying centres on the attitude indicator (AI), an instrument that is fundamental to the pilot's knowledge of the aircraft's flight. It is the only instrument that shows unambiguous orientation in cloud, at night or in severe weather, when it will be a vital reference that helps the pilot to fly the aircraft within the structural limitations of the airframe, and it forms the basic reference for flight in emergency situations. The AI also shows the pilot directly the result of inputs from autopilot systems. The importance of the AI is such that it should be clearly displayed at all times, and not partially covered by other symbology such as flight path vector. Modern electronic displays of the AI are generally easy to read, with appropriate colours for sky and ground. The AI should continue to be the centrepiece of future instrument displays.

3-6 The airspeed indicator (ASI), altimeter and VSI have suffered from being adapted to strip displays. In this form they lack the pattern information that is given by a rotating pointer on a fixed circular scale whose angular position can convey so much information at a glance. The use of a prominent pre-set bug may provide some short-term pattern information but it does not provide any information to update the overall mental picture maintained by the pilot. Strip presentations are not the best form for instruments that show rate information (Ref. 2).

3-7 The fact that there appears to be two conventions for the ASI scale, with high numbers at the bottom or at the top, is indicative of uncertainty in the philosophy behind the design of strip instruments that designers have perhaps been forced to introduce because they will fit on a PFD. With the former design solution, pitching the aircraft will cause the speed and altitude scales to move in opposite directions which may be confusing during take-off and initial climb. Opinion seems divided between the intuitiveness of the two designs in showing the sense of an error from a pre-set value, although the scale with high numbers at the bottom does have the advantage of displaying the same pattern as a fast/slow counter. The fact that there are such variations in opinion suggests that future instrument design should take advantage of technology that will provide a larger screen for the PFD, and allow the use of circular dials with pointers laid out in the traditional "basic T" fashion. Codes of practice should, if necessary, be altered to recognise the advantages of such displays, which have been demonstrated experimentally for some years.

3-8 A single pointer and dial presentation with a digital speed readout gives the pilot both a feel for changes in airspeed and accurate acquisition of a required speed. On aircraft with a large speed range it is possible to design the scale to alter with every half revolution of the pointer, as was demonstrated very satisfactorily in the UK some years ago, and speed bugs can be presented around the scale so that they are in view for longer than is possible with strip instruments. High speed and low speed marking can also be accommodated, and indeed always should be; graphical presentation of the flight envelope is one of the benefits of glass cockpit displays. Another benefit is the ability to display performance-related speeds based on incidence, calculated by the FMS. This avoids the need to obtain these speeds from graphs or tables with attendant risk of error, and ensures the most economical aircraft operation.

3-9 The introduction of the servo-altimeter was a great advance over the three-pointer presentation. It is easy to read, and to interpret rate of change of altitude and to acquire a specific height. Any movement of the needle immediately highlights even small deviations from the required datum, giving accurate height holding. With the strip altimeter the actual altitude is given by the digital readout rather than the pointer making deviation less readily observed, and only a small part of the scale can be seen at any one time. As with the ASI a strong case can be made for reverting to a circular scale with a moving pointer, using modern technology to enhance the display.

3-10 The VSI has sometimes been given a reduced role in the latest flight systems, and it tends to be lost in the clutter of the PFD. However, it is still a vital instrument because it provides information on rate of change. If driven by inertial reference systems as on the B757 for example, it gives instantaneous vertical speed which in turn allows accurate rates of climb and descent and assists the pilot in maintaining level flight. It should be clear and easy to read, uncluttered and of adequate size. One manufacturer has developed a very effective combined VSI and counter/pointer altimeter and others are providing a combined VSI and Traffic Alert and

Collision Avoidance System (TCAS) display. Since the continuing development and introduction of TCAS will be important not only in today's air traffic environment but also in the context of an autonomous aircraft operation as discussed in Chapter 6, the design of the VSI is of particular importance.
3-11 The remaining flight instrument in the traditional sense is the turn and slip indicator, the "turn" part of which has become obsolete in modern aircraft. A standardised position for a slip indicator, however, should be found, since this instrument enables the pilot to monitor and co-ordinate rudder input following engine failure. A position above or below the bank indicator would probably be suitable.

Flight directors
3-12 Flight Directors have become an integral part of the PFD, and are usually either crossed wire or V-bar type. While the former is clear and simple to use, it is not really a "director" at all, since it gives no information about the nature of the manoeuvre commanded, whether the demand is satisfied or not. Is a roll demand, for example, because excess bank has been applied or because the required heading has been achieved? The V-bar system does not have this disadvantage, nor did the ring sight-to-pointer system of the 1960s. Perhaps the flexibility of modern technology would allow the development of alternative flight directors, keeping them simple, taking great care in the way in which they interface with other systems such as autothrust and autopilot, and ensuring that the basic flight instruments remain clearly visible.

Navigation displays
3-13 It has already been noted that one of the benefits of modern technology has been the introduction of the pictorial navigation display (ND). If, as is usual, this is positioned beside the PFD, supplementary heading information in the form of a compass rose or arc should be available below the AI on the PFD. It should be remembered that arc displays are more intuitive to use than straight-line displays. While it remains necessary to use ground based aids such as VOR for non-precision approaches, or to resolve map shift, a full compass rose display should be available to each pilot on which VOR and/or ADF needles can be fully displayed. It should also be possible to display selected DME values on the ND independently of the associated VOR needle. Navigation displays that can show the present position of the aircraft in the centre of the picture, as well as north oriented and track oriented provide a useful flexibility, for example where a circuit is being flown. The vertical profile is commonly displayed by writing the height constraints by the appropriate waypoint on the ND. An alternative method that provides a separate vertical profile display in the lower part of the ND might, if developed, be considered more natural and easier to use. While pilots usually anticipate any problems in meeting a required vertical profile, a system that would draw attention to difficulties beyond the active waypoint would be welcome. The controls for the PFD and ND should be mounted on the glare shield rather than the centre pedestal or console, avoiding the need for the pilot to turn and lower his head when making selections, such movement leading to disorientation when the aircraft is changing attitude or heading. The position, shape and selections of the controls should be standardised, thus eliminating the need for the pilot to learn new controls each time a new aircraft type is flown. A common standard for symbology would also help to reduce training time and costs.
3-14 There is a tendency for NDs to be cluttered with unnecessary data and this should be avoided. The presentation of data on the ND for orientation should be both pilot-selectable where possible, and integrated with the flight management philosophy adopted by the manufacturer (see chapter 6). A simple example of this sort of philosophy is the presentation on the B757 ND of symbols showing the projected vector of the aircraft over the next 30 seconds. It is simple, clear, intuitive and very useful. It is also important to include the cardinal compass points, N,S,E,W, on the ND; there is evidence that such basic data might have helped the pilots maintain their orientation during a descent in mountainous terrain that ended in a fatal accident.

Systems displays
3-15 The introduction of glass cockpits has allowed an enormous amount of information to be displayed in modern flightdecks, and the continuing development of computing power will permit ever more comprehensive information to be displayed in the future. Depending on the space available, aircraft may have screens dedicated to secondary information such as engine and systems readings, systems schematic diagrams, and normal and abnormal checklists; others may use a multi-function display (MFD) that is primarily used as the weather radar. Whatever the layout the systems should be simple to use and the presentation appropriate to the task. The primary use of the display such as weather radar should not become lost in the desire to present other systems on the same screen.
2005 Comment. There is no doubt that the advent of Terrain Awareness Warning Systems (TAWS)/Enhanced Ground Proximity Warning Systems (EGPWS), has provided a significant advance in flight safety. It has given rise to a requirement that it is to be fitted to most turbine powered aeroplanes. This requires an additional electronic display on the instrument panel where it can be amalgamated with the weather radar display. The design of the display and its controls needs careful consideration if conflicting messages are not to be confused.
Real values of temperatures and pressures on systems diagrams can allow the pilot to monitor trends and assess relative values, assisting in fault diagnosis. An appropriate choice of strip or circular gauges must be made, the preference for circular instruments being noted where rate of change information is needed, for example on primary engine gauges showing power in the form of revolutions per minute (N1) or engine pressure ratio (EPR). Pointers on circular instruments are generally preferred to originate in the centre of the instrument, as on the N1 gauges on the A320, rather than offset as on the EPR gauges on the B757. Consideration should be given to standardisation of the position of the pointer for specific readings so that a glance can confirm normal operation. Colour coding of limiting values on engine and systems instruments are of great value in keeping the operation simple and unambiguous. Coloured marks can convey a great deal of information.

Checklists
3-16 The use of checklists on screens can generate more problems than it solves, and care must be taken not only with the design of the checklist presentation and the software that drives it, but with the way the pilot must manage it particularly in the multiple failure case. A checklist on a systems screen should not be any more difficult to manage than a conventional hard copy checklist; at least one current system provides so much information that the pilots often have difficulty using the checklist and dealing with a serious emergency at the same time. Bear in mind that in a two-pilot crew the pilot reading and actioning the checklist must also keep the handling pilot informed about what is happening, and this is very difficult if he is inundated with information so that he has to be selective in the information imparted to his colleague. Multiple failure situations may also reduce the screen space available on which to display the checklist, further compounding the problem. Emergency checklists that move up the screen requiring only the top line to be read and actioned in sequence seem logical initially, but the natural ingrained habit of reading from the top down the list, each line in turn, can take over in times of stress leading to missed actions or a wrong sequence of drills. While simple everyday checks are easily actioning from screens, abnormal checks might be better done from a hard copy.

Summary
3-17 The following points should be considered in the design of flight instrumentation:

a. The primary flying instruments should be dial presentation. When assessing pilot preference versus strip instruments the relative experience of the pilot being questioned should be considered. If the only large transport aircraft a young pilot has flown has strip instruments he will probably say that they are satisfactory. A more experienced pilot will be able to relate the strip instruments to the analogue ones found in older aircraft.

b. The human factor element in the art of flying must be considered in flight instrument design, and the pilot should not be external to the operation but always considered as an integral part of it.

c. The systems should be simple and instinctive to read, interpret and operate. There should be no ambiguity, and the methods of operation should be self-evident and intuitive in use. Any instrument mode selection must be unambiguous and the function clearly stated.

d. The pilot can only absorb a certain amount of detail at one time, so there should be a limit on the quantity of data to be interpreted and used, particularly in the event of an emergency.

e. All formats and layouts, colour coding, controls position and operation should be standardised.

f. Designers and manufacturers should fully and clearly understand how line pilots, who should be consulted at the earliest stages of development, use instruments. The views of the line pilot, and the way he operates the aircraft, may not always coincide with those of technical managers and industry pilots. The abilities of a line pilot of least competence must be the prime consideration.

3-18 By designing simple instrumentation and systems it should be possible for a pilot to graduate from primary training to the most modern aircraft in a common and familiar environment. This will build confidence, experience and proficiency in a shorter time than if new systems and instruments have to be learned at each stage, and will allow emergency situations and periods of high workload to be easier to deal with. In fact the opposite state of affairs exists today, with each new aircraft incorporating instrumentation and systems fundamentally dissimilar to the last, each requiring new skills to be learned and remembered. One of the primary objectives of future instrument design should be to adapt the system to the pilot rather than adapt the pilot to the system. If the former is done the pilot will be able to utilise his basic training and experience to solve problems and reduce the need to carry out complex procedures specific to one aircraft type.

4. FLIGHT MANAGEMENT SYSTEMS

Introduction

4-1 The FMS discussed in this chapter, and the autopilot and autothrust systems discussed in the next chapter, may be taken together because of their interdependence; the FMS usually having control over the autopilot and autothrust systems if so delegated by the pilot.

The pilot interface

4-2 The FMS allows the pilot to interface through a keyboard and screen (the control and display unit (CDU)) with the aircraft navigation and performance computers, and it can control the aircraft through the autopilot and autothrust along a pre-set flightpath in four dimensions. This provides the opportunity to reduce pilot workload, but in current aircraft it tends to be most effective during periods of flight such as the cruise when workload is already low. When workload is high, the FMS tends to increase it further, to the point, in some designs, where the operation would be simpler and safer without FMS. The key to a well-designed FMS is in the quality of the interface, primarily with the pilots, but also with the other automation that can control the aircraft. It is essential that the "thought process" of the FMS matches that of the pilot, and does not require knowledge or techniques that are unnatural or counter-intuitive. The pilot must be informed what is happening when the FMS is controlling the aircraft, particularly when major changes are occurring, but need not be given information that is obvious. The logic behind the presentation of information to the pilot should match the interest and priority that would be given to it by the pilot had the information come from a navigator, flight engineer or radio operator. It should also be borne in mind that communication between pilots can be more difficult with FMS equipped aircraft, because it may not be apparent to one pilot what inputs the other

pilot is making to the FMS. The amount of displayed cross talk between two FMS installations is therefore an important part of the design.
4-3 It can perhaps be seen from the previous paragraph that if the design is unsatisfactory the value of an FMS installation to the pilot may not be as high as initial impressions suggest. While it is granted that the pilot is supplied with a great deal of very accurate information, this is of benefit only if it is easily accessible and is information that is actually needed. Furthermore, the principles on which the FMS is installed — reduced workload and greater accuracy of navigation and performance — are only valid if there is no increase in workload at times when aircraft handling is downgraded as with an engine or systems failure, or when ATC workload is high, as when manoeuvring in a busy terminal area (TMA).
Experience suggests that these criteria have not been wholly met in current FMS installations, and that the value of simple area or inertial navigation systems and performance data computers that were common before FMS became widely available, was considerably higher. Setting up was simple, accuracy entirely acceptable and far better than with traditional methods of navigation, and no extra workload was involved when the pilot was under pressure. An FMS such as that in the A320 is such an integral part of the aircraft operation that it cannot be ignored no matter how busy the pilot is, and workload is increased even when such everyday exercises as a non-precision approach are being performed. (See para. 1–3).

4-4 The design parameters in an FMS should be dominated by one requirement above all others - that of making the interface with the pilot as simple and logical, from the pilot's point of view, as possible. A good interface will reflect a pilot's mental process that takes place when maintaining a sense of orientation and position when flying in cloud. Para. 1– 13 sets out some guidelines for human centred automation (Ref. 3), and one of these states that:
"Automation should be designed to be simple to train, to learn and to operate. Simplicity, clarity and intuitiveness should be among the cornerstones of automation design, to make it a better and more effective tool".
Nowhere can this apply more than to FMS, and the following paragraphs will discuss features of current FMS installations, and relate them to the pilot interface.

Features of the control and display unit
4-5 The CDU, through which the pilot communicates with the FMS, usually consists of a small screen and alphanumeric keyboard. Para. 2–4 comments on the awkward operation of such keyboards, and the improvements that might be offered by the use of a different keyboard, and roller ball or "mouse" control. The Society of Automotive Engineers (SAE) also recommend (Ref. 6) that consideration be given to alternatives to the keyboard, such as track ball or joystick. Certainly, the cursor and menu system used on a DME/DME area navigation system installed in the B737 by a major airline, although admittedly controlling relatively few parameters, is very user-friendly. Whatever the method used, future development of CDUs should aim to keep typing to a minimum, since this is a time-consuming task that is prone to inaccuracy. One of the most effective ways to achieve this may be seen in the B757, where pressing a line select key will write that line, or an appropriate part of it, into the scratch pad. This can be contrasted with the A320 CDU, where almost all entries have to be typed into the scratch pad.
4-6 There are some other fundamental features of FMS design which will determine the success of the pilot interface, and these are all in line with the SAE recommendations (Ref. 6) and worth emphasising, the first being the use of an "execute" key. This allows the pilot to review the entry made before it takes effect, and is probably used most when amending the en-route flight plan as a result of ATC instructions. The apparent disadvantage of this facility is that there is one more keystroke to make to achieve the desired result, but in fact the logic is entirely in keeping with the pilot's thought process, which is to cross check that an action is correct before carrying it out. The lack of an execute key on the A320 causes errors to occur which are not made on the B757.
4-7 After the need to keep typing to a minimum, and the provision of an execute key, the next important design feature to consider is font size and type. Font size is used to provide emphasis,

and it should be remembered that this can be effective in all conditions, whereas the use of colour may not. The most important line on the CDU is probably the "TO" waypoint, and this should be in larger font size than any line above it, such as the last or previous waypoint. The use of "ditto" marks should most certainly be avoided, since they are too small to maintain the continuity of the information across the line, and require the user to refer to another line or even another page to determine the value to which the marks refer. Except for the line before the "TO" waypoint, font size can be uniform over the CDU, and should be as clear and large as possible.

The use of colour on the CDU is usually linked to symbology on the PFD or the ND, and may be used to convey specific information as well as to give emphasis. While this is useful up to a point, it is not a substitute for the use of clear symbology and correct font size in the first place. Some colours should not be used together on one screen because it can be difficult to differentiate between them, and the contrast between colours will always be reduced at night when the brightness is turned down. The A320 CDU uses white and green font that, at night, becomes almost monochrome. It is significant that the B757 CDU with clear font in monochrome is easier to read than the A320 CDU that uses colour.

4-8 The FMS function most used by the pilot, and which is of most use to him, is that of navigation, with the route usually displayed on the ND. The database will hold the most used routes, as determined by the operator, with the facility available to build up a route manually by airway and waypoint. The interface with the pilot may be at its most demanding when this latter facility is used, often when time is short and an unfamiliar route has to be inserted using a procedure that is seldom practised. The blank line on which each section of the route is written should maintain its position on the CDU screen, with each completed line moving automatically out of the field as it is entered. Definition of waypoints by any method (bearing/distance, latitude/longitude, bearing/bearing, etc.) should not require a rigid pattern of keystrokes; the usual problem encountered is insertion of latitude and longitude. The position defined by these numbers should be obvious from the route being constructed, so an error in format should not necessarily result in rejection of the data. If any input is rejected, where possible the reason should be given or a more correct alternative offered. The bare message "format error" is not very helpful on its own! When a route is being checked for accuracy, it is helpful if "pages" can be "turned" by one key stroke, rather than having to be scrolled through line by line — like typing, a laborious process. To aid checking, every line should include track and distance to the next waypoint, or cumulative distance from each waypoint to the destination.

Enhancing features

4-9 To sum up so far, the three major factors contributing to a good interface with the pilot are a minimum of typing, use of an execute key, and the use of font size rather than colour for emphasis. Additionally, data should be simple to insert, and messages displayed by the FMS should have real meaning. Other features that enhance the use of FMS include a simple and logical method of initialisation, whereby it is obvious when all parameters have been entered. The A320 requires up to ten entries to be made on one page, which have first to be extracted from a performance manual or loadsheet, then typed into the scratch pad and inserted into the FMS by line select keys, one item at a time. A change of runway before takeoff can require any or all of these figures to be changed. This cannot be said to be in accord with the guidelines referred to in paragraph 4-4 above, and it would seem desirable that takeoff performance data extraction is either kept at a very basic level using tables and airspeed cursors, or integrated completely with the FMS and produced automatically from the database. Electrical power failure or transfer should not affect the presentation of takeoff speeds during the takeoff run. The insertion of en-route winds into the FMS by datalink would save a great deal of time on long flights; the ability to conduct diversion predictions is also important. A facility that presents the pilot with the stored values of winds encountered during the previous descent, which can be accepted and entered for use during the next climb by just two keystrokes, is useful and simple to use. Similar logic would provide for radio aids selected by the pilot through the CDU to be determined as sensible by the known position and future route of the aircraft, as held in the FMS.

4-10 To complete this discussion of the day-to-day use of FMS, it may be helpful to emphasise some other features that are particularly useful. Firstly, temperature deviation should be displayed, preferably somewhere that is continuously in the pilot's view. Secondly, a "Fix" page should be available on the CDU, to allow radials and "abeam" positions from selected waypoints to be displayed on the navigation display. Thirdly, a quick method of showing a position a given distance before a waypoint, on current track, should be provided. This is frequently required by ATC for vertical separation. Fourthly, the cruise information on the CDU should include on one page: track and distance between every waypoint (or cumulative distance to destination) and estimated time of arrival (ETA) and fuel remaining at every waypoint. It is unnecessary to include cruising height and speed on each line — the pilot should be well aware of these parameters! Fifthly, there should be a "delete" or "return to previous condition" key, making rectification of errors simple.

Vertical navigation

4-11 The use of FMS for navigation includes a "vertical" element, both for performance calculations such as optimum cruise altitude and speed, and for tactical calculations such as optimum descent point. While there may be some merit in these facilities being included, in many parts of the world the ATC environment seldom permits their full use. An autonomous aircraft should allow less restrictive air traffic management but this state of affairs has not yet evolved. Cruise levels available will often be restricted and it must be obvious to the pilot which is the best alternative. Descent calculation may be pointless if the start of the descent is determined by ATC requirements, and the insertion of data to calculate the descent has achieved nothing. What is more important to the pilot is a display of the climb or descent profile, in relation to tactical ATC or procedural restrictions, that can be easily modified and that is always displayed. It should not be dependent on whether the aircraft is either on a fixed heading or being guided by the FMS. The approach phase of flight is one where the accuracy of the FMS and the source of the navigational data it is using should be provided, and any downgrading in accuracy should be flagged.

Summary

4-12 The provision of FMS in modern aircraft has made many tasks of navigation easier and more accurate, but at the same time has brought problems of its own. Design logic does not always fit in with the pilot's way of thinking or with the everyday operation of the aircraft, a point that has already been made in para. 1–3. Feedback to the pilot can be critical, not least to give confidence in the operation of the system. Perhaps the most important consideration for the future, as FMS becomes more integrated into the design of the aircraft as a whole, is the dramatic increase in workload that can result at times when the operation needs to be kept as simple as possible. Maybe the better interface to be found in "knowledge based systems" or "artificial intelligence" will allow the full potential of FMS to be realised (see Chapter 6). The next generation of FMS should be less integrated with other aircraft systems, far simpler to operate at all times, and with better chosen features.

5. AUTOPILOT AND AUTOTHRUST

Autopilot development

5-1 The autopilot was first introduced as a simple device to control the aircraft attitude, allowing the pilot to attend to other tasks without needing to give constant attention to flying the aircraft. Technology allowed functions such as height and speed locks to be introduced, and by the 1950s it was possible to use the autopilot to fly an approach coupled to the ILS. This naturally led to autoland capability, but even then the autopilot was still a tool to help the pilot, simple to operate and with relatively few modes. The Trident, for example, operated to Category 3b minima, yet the autopilot provided only IAS/Mach lock, height acquire and hold, rate of descent selection, heading or track hold and separate localiser and glideslope capture. This is no longer true, the latest autopilots including so many modes that the pilot may become confused, especially as some modes can change without a pilot input. Indications are provided to inform the pilot which autopilot modes are in use, but again, this can include so many alternatives that it is itself confusing. It is time to reappraise the philosophy behind autopilot design, and consider whether a return to simpler systems would provide a better tool for the pilot. Some pilots would suggest that aircraft such as the 500 series L-1011, or the Trident referred to above provided a good balance of autopilot performance, facilities and simplicity.

Control feedback and authority

5-2 The prime task of the autopilot is to control the aircraft in a manner determined by the pilot. It is therefore reasonable that there should be adequate feedback through the controls so that the pilot can monitor what is happening, particularly during critical phases of flight. Older aircraft have controls that are moved by the autopilot, but in the A320 for example, there is no movement of the side stick by the autopilot. The elevator trim wheels, however, do move, and since they are comfortably within the pilots' view provide some feedback; this might be considered the minimum acceptable in normal flight. In abnormal flight, following an engine failure, rudder pedal movement must be provided to allow the pilot to monitor autopilot rudder input, and to transition smoothly to manual flight when disconnecting the autopilot. The argument for the amount of feedback required is confused by the fact that most pilots confirm that the autopilot is making the correct inputs to the control surfaces by reference to the flight instruments as well as to the flying controls. However, there should always be redundancy built into the channels of transmission of vital information and the maximum number of sensors possible should be available to the pilot. The point cannot be considered in isolation, since feedback of autopilot inputs is also important when considering mode annunciation, (see para 5-7).

5-3 The control inputs made by the autopilot must strike a balance between being too powerful, and not powerful enough. The former may give an uncomfortable flight, and the latter may make it difficult to attain the desired flightpath, even allowing airframe limitations to be exceeded despite the observance by the pilot of standard operating procedures. Initial autopilot engagement should be in "wings level" and "pitch attitude hold" modes, these giving the safest condition should no other mode be engaged immediately. A firm pitch response is needed to control deviation from the desired flightpath when changing configuration, usually during the approach to land. Rate of descent control is often in use at this stage of the flight, and that on the B757 is a good example of firm accurate control. Pitch control during the descent from cruise altitude should be smooth enough to avoid discomfort when the descent is not continuous.
During climb, transition from indicated airspeed to Mach number should not take place at a fixed altitude, but at a fixed air-speed/Mach value. For example, if a climb at 300 knots normally becomes M.78, then so too should a climb made at 280 knots due to turbulence. This avoids the possibility of the latter stages of the climb being made at too low a Mach number, which can happen on the B737. Application of bank, particularly below 250 knots, should be reasonably firm to allow prompt compliance with ATC requirements. It is also very convenient to have a pilot-selectable bank angle, as seen on the B737, which allows 25° or 30° of bank to be achieved for terminal area manoeuvring, and 10° or 15° to be used in the cruise.

5-4 Some autopilots of the 1950s and 1960s had separate ILS localiser and glideslope capture which usually allowed a smoother transition on to final approach than is sometimes the case with modern aircraft. Some current autopilots prevent capture of the glideslope before the localiser, which a pilot may wish to do, and will sometimes capture both at the same time. It is important for passenger comfort that both localiser and glideslope capture are smoothly effected, whether taking place separately or simultaneously, with bank applied gently. A tendency to pitch up into the glideslope when capturing it is another undesirable characteristic that can surely be avoided. Perhaps modern systems have enhanced reliability at the expense of smooth anticipation.

Autopilot selectors

5-5 Autopilot controls are usually placed on the glare shield between the pilots, allowing easy monitoring of the selections, and being within reach of both pilots. With the introduction of more modes of operation the controls have become complex and more susceptible to mis-selection. Safety critical controls, such as the height selector, should control the minimum of functions, and the system seen on the B757, using separate buttons to activate some modes, is better in this respect than that on the A320. On this aircraft, one knob is used to select height in hundreds or thousands of feet and to initiate climb or descent in "open" mode or in "managed" mode. Similarly, one knob selects either vertical speed, in feet per minute, or flightpath angle in degrees. If multifunction selectors are unavoidable, then there are too many modes included in the autopilot. An indication of flightpath angle may be desirable, but is it necessary to include it as a selectable autopilot mode? Is it necessary to include selectable rate of climb? Bear in mind the incidents that have been caused by use of this facility (Ref. 4).

5-6 The indicator windows associated with selections of heading, height, airspeed, vertical speed etc. must be easy to read and operate without lag. The LCD type of indicators that are found on the A320 are excellent in this respect, while the older mechanical displays sometimes take a measurable amount of time to settle before they can be read and readjusted if necessary. A pre-selectable altimeter setting facility, as fitted to the A320, is an excellent design feature that reduces workload and enhances safety. The selector knobs themselves are usually too similar in size and shape, and most pilots have mistaken one control for another at some time. The knobs should be dramatically different in shape and not just variations of a circular form; perhaps the accepted conventions for this type of control should be reconsidered.

Mode indications

5-7 In order that the pilot knows which autopilot modes are engaged a mode indicator is provided, usually in front of each pilot. While this seems at first sight to be quite straightforward and useful, there may be so many modes annunciated at one time that confusion sets in. The problem is exacerbated by the need for the pilot to look to the glare shield for the autopilot controls and some indications such as height or speed selected, which may or may not be repeated elsewhere, and to the mode annunciator to confirm the modes engaged. There would seem to be a requirement for some mode annunciation to be associated with the autopilot controls, as well as with the instrument displays, which is where they are on B757 and A320. It has already been suggested that pilots obtain most feedback from the flight instruments showing what the aircraft is doing, and that confirmation of mode engagement might be sufficient if given by illumination of buttons and lights associated with the selectors on the autopilot control panel. Current thinking is that such illumination only shows that the button or switch has been operated, not that the mode has been engaged; this may well have been a contributory cause of the L-1011 accident in the Everglades (Ref. 7).

5-8 One solution to the problem of ever increasing numbers of mode indications might be the adoption of the same philosophy that is used to group written warnings in general terms on the B757. Here, an engine shut down brings up only one message - the engine is shut down. Other messages that are consequent upon that condition, such as "low oil pressure", are assumed to be realised by the pilot and inhibited. A mode annunciation appropriate to ILS capture might thus show only "ILS", not "localiser" and "glideslope" separately as is usually the case on current aircraft. If there are too many modes annunciated, pilots will tend not to read them, as might have been the case in the A320 accident at Strasbourg, (Ref. 8), where the inadvertent selection of "vertical speed" would have been shown but might not have been observed. Some pilots feel that mode indications displayed at the top of the PFD are less naturally observed than those displayed in the lower part as they are on the B757. Consideration might also be given to making the amount of detail shown by the mode indications more appropriate to the workload and stage of flight.

Autopilot summary

5-9 The autopilot should be designed as a tool for the pilot to use to reduce workload, and permit attention to be given to other tasks. As such it should be kept simple and not become a complex system that generates its own set of problems. Interaction by the autopilot with other systems such as FMS and autothrust should be in a way that is logical to the pilot and in accordance with intuitive human responses. The authority of the autopilot should be appropriate to the stage of flight, and be carefully integrated with configuration changes. Separate capture of localiser and glideslope would make for a smoother and easier approach, and glideslope capture from above should be possible without the pilot needing to switch between modes. Mode indications should be as few as possible, and associated with the autopilot controls as well as the flight instruments, which are instinctively monitored by the pilot and provide independent feedback.

Autothrust

5-10 Full flight authority autothrust systems seem generally to work well without generating too many problems of their own, although accuracy of speed holding sometimes leaves much to be desired. Some systems are more instinctive to use than others, and there has been much discussion about the relative merits of the "non-moving" thrust levers on the A320. Since moving thrust levers are intuitive and give a tactile feedback to the pilot, it seems preferable that autothrust should operate in this way. The lever angle is always matched to the power setting so autothrust disconnection is quicker, being done without the need to align thrust lever angle with engine power indications before pressing the disconnect button. It should also be kept firmly in mind by designers and pilots alike that a modern autothrust system will reduce power according to an electrical signal, whether it makes sense or not.

5-11 A "command segment" on the primary power indicator (EPR or N1), as used on the B757, is a useful feature whether thrust is set manually or automatically. The selection of take-off and go-around power should involve a simple movement, advancing the thrust levers to an appropriate detent. The "palm" switches on the B 757 may be awkward for some pilots, and others probably find the finger-operated buttons on the B737 difficult too.

The go-around manoeuvre

5-12 The go-around manoeuvre is one that should be recognised as requiring stability and good response from the aircraft, autopilot and autothrust.

The two stages of go-around thrust available on the B737 is an excellent way of providing a pilot controlled application of go-around power according to the need at the time, and helps avoid over-rotation of the aircraft. The B757, on the other hand, can provide for modulation of aircraft rotation and initial rate of climb by automatically varying the thrust, a method that tends to promote an unstable manoeuvre. While appreciating the aerodynamic problems associated with the high power outputs of modern engines mounted under the wings, the go-around characteristics of older aircraft with their natural, gentle pitch up with application of power might be something that future aircraft could emulate with advantage.

5-13 The response of the autopilot, autothrust, and airframe must be considered not only in the case of a go-around from a discontinued autoland, but in other circumstances such as when a hand-flown approach, with or without autothrust, is discontinued. Go-arounds because preceding aircraft are slow to clear the runway after landing are common occurrences, and pressures on air traffic management will doubtless ensure this situation continues. Autopilot, autothrust and FMS should not be so difficult to operate that such occasions result in very high workloads.

6. FUTURE TECHNOLOGY

Development of the autonomous aircraft

6-1 When new inventions and ideas have been suggested in the past there has often been a reluctance to develop them with enthusiasm, and a tendency to look at the negative aspects instead of the positive ones. In aviation particularly the rate of change of technology is not always appreciated, and an idea may not be developed because the technology required to make it work is not seen to be available. History demonstrates time and again that what has been dismissed at the time as impossible, unnecessary or too expensive, can soon become part of the everyday operation. Whereas in the past the perceived problems were usually mechanical ones, they are now tending to be computer software and human interface ones, the solutions to which require a broader outlook and a willingness to examine new ideas in a positive way.

6-2 Throughout this Paper the themes of the autonomous aircraft and human centred automation have been evident and this chapter takes these ideas further. The logic behind them has been discussed already, and the methods of attaining them are becoming available very quickly; some are examined below. Although the idea of strategic Air Traffic Management (ATM) and autonomous aircraft operation may seem far-fetched, it should be remembered that military aircraft operate as autonomous flights, often in a very hostile environment, and have used such equipment as head up displays (HUD) for some time now. The use of TCAS was almost science fiction just a few years ago, but now offers the opportunity to alter the thinking behind the whole system of ATM. Is collision avoidance and separation actually as difficult as people think it is?

6-3 From another point of view, TCAS and Ground Proximity Warning Systems (GPWS) might be seen as good warning devices that wouldn't be needed if the right procedures, sensors and equipment were in use. Why are aircraft operating with strategic equipment such as FMS in an environment that is dominated by tactical procedures? (see para. 4–11). For the development of new technology to be successful it should take place in the light of the answers to the right questions.

6-4 Practical and financial considerations suggest that, ultimately, future aircraft operation will be autonomous to the extent that on-board systems will allow a cost effective route trajectory to be flown and a landing made at any runway, without the use of ground facilities such as VOR, ILS or microwave landing system (MLS). For cost reasons, the limitations on take off and landing set by low visibility will be resolved by equipment installed in the aircraft rather than associated with each runway. Only by developing the equipment in the aircraft rather than on the ground will it become possible to operate to airfields and runways which presently have few facilities because of cost or physical restrictions, and this is acknowledged by both airlines and certificating authorities in listing the ability to monitor the approach path to an airfield with no ground based aids among the benefits obtained from the use of HUD.

6-5 Future ATM must evolve from today's tactical methods that involve essentially short-term control by R/T, to a strategic method that monitors an aircraft flying a predetermined trajectory. The exact methods and the timescale involved are beyond the scope of this paper, but the principle would seem to be in accordance with most ideas put forward for the development of ATM. Over the North Atlantic and the Pacific, Automatic Dependent Surveillance (ADS) utilises data-link to provide information to ATC that allows position and track keeping to be monitored, ultimately permitting reduced separation. The use of TCAS technology for en-route station keeping is also under consideration, and it is possible to use Mode S to provide, for example, information on adjacent aircraft speed, height and heading for presentation on the TCAS indicator or the navigation display. These developments are basically in sympathy with the philosophy of an autonomous aircraft, and might be considered essential for the operation of the next generation of Supersonic Transport (SST), (see para. 7–6). It is emphasised, however, that the use of data-link to give tactical commands directly to the FMS is not considered desirable; data-link should be used to communicate, not control, because control inputs that are not initiated by the pilot tend to remove him from the situational awareness loop, and break down his mental picture. The aircraft will therefore need to be able to fly sufficiently accurately in four dimensions, and it seems likely that developments of current FMS using a form of satellite and/or inertial navigation will be suitable. Indeed, research aircraft are already able to demonstrate this capability.

2005 Comment. Satellite and inertial navigation have become accepted as the main means of navigation away from domestic areas and when coupled with TCAS supported by Mode S Enhanced transponders will enable 4D trajectory planning and navigation for free routes. However before this comes to fruition safeguards will need to be in place to ensure that acceptable safety standards are maintained. One of the accepted ways that has been developed is for the Required Navigation Performance (RNP) of specific navigation equipment to meet the accuracy necessary for operations within defined airspace. ADS-B is also being developed for aircraft to 'see' one another when within defined ranges by broadcasting position, course, speed and altitude that is then displayed as a relative position on a cockpit display; it will be complementary to TCAS as it will not give traffic advisories (TA) or resolution advisories (RA). Ground stations can receive the information when the aircraft is out of radar range so giving ATC a wider 'picture'.

Flight management using knowledge based systems

6-6 The current style of route presentation on flight deck displays will become meaningless if a long direct route is being flown; even now situational awareness has to be enhanced by the pilot on some sectors where direct routings of two or three hundred miles are given. Displaying VOR or airfield positions from the FMS database does this, where available. The computing power of current FMS falls far short of that now available to designers of a new aircraft because of the long lead times involved in design and certification, and there are opportunities for future systems to take advantage of the enormous improvements in computer technology that are available today.

A digital database displaying topographical, cultural, and operator defined data could provide en-route positional awareness related to terrain or airspace boundaries, and offers a method of flight management that could make use of knowledge based systems to enhance the pilot-machine interface. Topographical databases, derived from mapping surveys, are becoming available, and may contain details down to the size and position of individual buildings. By using the navigation display itself rather than the FMS keyboard for database interrogation, it is possible to enlarge from an en-route display of, say, 1:1,000,000 scale, showing topographical shading, navigational waypoints and airspace boundaries, to the layout of the runways, taxiways and obstructions of an individual airfield. The amount and type of information is selectable and can include airfield data such as runway dimensions, height above sea level, and radio aid and communications frequencies.

The topographical detail can be incorporated into the GPWS framework and displayed in the form of a lattice overlay superimposed on an approach path either "head up" or "head down". Use of such databases has already been demonstrated in the UK, and would appear to offer a solution to the problem of control and display of the large quantity of information that can be made available to the pilot. It can also interface with terrain avoidance systems; head up displays, enhanced vision systems to aid ground manoeuvring in low visibility as well as during low visibility landings, and electronic library systems.

6-7 There are many criticisms of current FMS design that may be traced to the unsuitability of the system-pilot interface for the task for which it is used. The keyboard is small and awkward to use, and the method of operation and logic incorporated are not always compatible with the pilot's thought processes, which suggests that more research on pilots' mental models is needed. It will be necessary to evolve the FMS design in line with the navigation and systems management as described in the previous paragraph, getting away from the need to access information by detailed typing, and dealing instead with accessing information appropriate to a phase of flight in more general terms. Thus, an en-route diversion could be managed by marking the new destination on the navigation display that would generate the required, or most likely, route and the terrain below it, together with the layout of the airfield. Choice of runway would then show appropriate minima and performance data. It is the consequences of a decision that the pilot wants to know, not necessarily the detailed information on how the consequences are arrived at. Current systems require the pilot to arrive at the consequences of a decision by going through a laborious and error-prone procedure that often has to be done in an illogical sequence during periods of high workload.

Enhanced terrain awareness

6-8 To provide a safe approach with respect to terrain the pilot needs to see the ground, in fact or as a picture. The digital database referred to in para 6-6 can provide the necessary information which can present the terrain as a stereoscopic lattice on which the descent path may be superimposed. The view may take one of several forms, but should be aligned with one of the two most common mental images used by pilots — the "Gods eye" view, from above and behind the aircraft, or a "plan" view, as if the pilot were looking at a moving map display. Not only would this system relate to the GPWS parameters thus providing the system with the ability to "see" terrain ahead, but it would also provide the essential relationship between the representation of the aircraft and the terrain that allows the pilot to maintain orientation. In conjunction with an augmented GPS navigation system, an approach to current Cat 1 minima could be made to any runway without the need for ground based facilities; bearing in mind the introductory paragraphs to this chapter, the present restricted coverage by databases and augmented GPS should not prevent consideration of these ideas.

See 2005 Comment in para 3-15

Head up displays and synthetic vision systems

6-9 To permit an approach below Cat 1 it is likely that some additional system will continue to be required, at the moment ILS and perhaps MLS. Both these are ground based systems, however, and unlikely to be installed at other than major airports (and then only on the most used runways and where terrain limitations can be overcome). An alternative philosophy is required that maintains the theme of an autonomous aircraft and head up displays (HUD) and enhanced or synthetic vision systems (SVS) should both be considered, as complementary systems. The former is already in airline service in the USA and certification standards are under review by the JAA; development of the latter is continuing to overcome its disadvantages. Both systems have the advantage of being independent of GPS, which may prove difficult to certificate to better than Cat 1 integrity even with augmentation.

6-10 HUD can be used to achieve lower approach minima by producing symbology to show where the runway is and where the aircraft is going, either as a prime source of information or as a monitor of the autopilot in poor visibility, and as a monitor of aircraft performance on all approaches. The generation of symbology to give an approach angle, or glidepath, enhances the safety of every approach, particularly when operating at night into poorly equipped airfields with no approach slope guidance. Any system must, however, be usable at any runway, and from any approach no matter how difficult. If millimetric wave radar or infrared sensors are used, they must cope with all weather conditions, variations in reflectivity and airfield characteristics.

6-11 Modern inertial and electronic systems can provide accurate symbology such as flightpath vector (FPV), runway position and flare cues. Visual display of parameters such as stick shake attitude and TCAS information are of great assistance to the pilot. It is obviously desirable that the symbology is the same whether used head up or head down, and consideration should also be given to symbology displayed during a go-around when the handling characteristics of the aircraft such as the amount of natural or inbuilt pitch up experienced when thrust is applied, are very important. The parameters displayed by flightpath vector symbology need careful thought; the most effective displays show mainly pitch information, as lateral information can lead to disorientation. In order that the non-handling pilot can monitor adequately any aid such as a HUD or take off performance monitor (TOPM), the system should be available to each pilot. The use of holography in the HUD offers significant improvements in the field of view available, but implies a monochrome display; until this constraint is removed, the trade off between colour and field of view would need to be determined.

6-12 There are two pieces of current technology that could be combined in an innovative way to solve the problem of controlled flight into terrain (CFIT). The terrain following navigation system in cruise missiles uses a mixture of sensors to compare the adjacent topography with an onboard model, and fix position to an accuracy of a few feet. Illustrations of this equipment were seen on television during the Gulf War in 1991. A transparent screen is available that can generate translucent computer graphics to be used with an overhead projector to give dynamic pictures on the screen. If such transparent screens were placed against the windscreen and side screens of a flight deck no projector would be needed. They could be used to generate a lattice picture of the terrain, switched on or off as required, and related to the real world by the navigational sensors and database on the aircraft.

The technology for multi-screen presentation of a single picture already exists and the viewing would be similar to a television or computer screen, overcoming the problems of sighting and collimating HUD equipment. This system would overcome the problems of instrument interpretation that result in the three-dimensional model of the real world in the pilot's mind differing from that available in the navigation displays.

Further benefits of HUD and SVS

6-13 Both HUD and SVS have potential for secondary use in ways that would not be justified as "stand alone" systems. Synthetic vision would aid ground manoeuvring in conditions of low visibility, and together with the display of airfield layout from the digital database already referred to would allow safe operation without the need for surface movement radar.

There are indications that the infrared sensors associated with SVS might be developed to give warning of windshear, clear air turbulence and vortex generation in mountain areas. Should TOPM become an operational requirement, the cues could be displayed to the pilot through the HUD. It is felt, however, that the provision of TOPM is secondary to the proper training of pilots in dealing with take-off malfunctions and emergency actions, and adherence to standard operating procedures.

External cameras

6-14 External aircraft viewing by means of cameras is under trial, and while being no substitute for well designed fire detection systems may well have some benefit in providing the pilot with more information on which to base subsequent action in an abnormal situation. The immediate problems of installation to give an adequate field of view, and the need to provide for operation at night and in cloud, will no doubt be solved in time. There is some concern as to how the information might be displayed and used in the context of existing emergency drills and procedures, in so far as it might cause pilots to depart from the established procedures. It should be sensible in the event of a severe malfunction to first use the cameras to establish as far as possible the extent of any damage, before closing down engines and operating fire extinguishers. The use of cameras to establish the extent of airframe damage following recent instances of engine separation on B747 aircraft could have been invaluable to the crews.

Summary

It is impossible to determine the many ways in which new technology might be used to improve the safe and efficient operation of aircraft in the future, but however it is done manufacturers and certificating authorities should consider each item not just in isolation, but also as part of a plan that will follow a clearly set out path.

The most important elements must be the replacement of FMS with knowledge-based systems, and the use of HUD and SVS to provide the approach and landing capability in any weather at any runway. The common link is an appropriate database and sensors. It is time to look beyond the choice of a landing aid that has to be installed at every runway that needs bad weather approach capability, and develop the equipment to allow an aircraft to land at any runway, in any weather, generating a safe approach path with its on-board systems.

7. CONCORDE'S SUCCESSOR

2005 Comment. The early demise of Concorde in 2003 and the lack of a foreseeable replacement, except maybe in the business aviation sector, have rendered this paragraph redundant. However, the principles will still apply if a new venture is forthcoming.

Background

7-1 In the subsonic environment a supersonic transport (SST) can fit in quite happily with subsonic aircraft. There are no specific problems in this environment that are unique to the SST. The one area that can cause a problem for Concorde is the fuel penalty when flying below minimum drag speed, which allows little scope to absorb delays in the airport terminal area. Subsonic aircraft can absorb such delays if excess fuel is carried although this is wasteful and costly. One solution lies in an ATM system that does not allow an aircraft to depart until it has been allocated an arrival slot at destination.

7-2 In the transitional phases of flight (climb and acceleration; descent and deceleration) there are certain features unique to a SST. For example, once the acceleration and climb has commenced it is not practical to level off at some intermediate altitude. The pilot also has to react with caution to any suggestions from ATC for vectors to avoid conflicting subsonic traffic through whose levels the SST is climbing, because this may give a sonic boom where it is undesirable. Likewise, the descent and deceleration phase of flight does not allow for flexibility once the process has started because it is necessary for the aircraft to be subsonic at a fixed point. Again, great care must be taken with the navigation to ensure sonic boom protection.

7-3 In the supersonic environment above 50,000 feet Concorde has enjoyed clear airspace of its own; this will not hold true to the same extent in future if 200 or 300 SSTs are flying around the world, and will add a further dimension to ATM. The main concern in this environment arises when a technical problem compels reversion to subsonic flight. There are two main issues here other than the immediate one of dealing with the problem itself by checklist action. First, whether one likes it or not the aircraft must descend into the subsonic operating levels with the potential for conflict with subsonic traffic. Second, in the case of Concorde a 30% range penalty will ensue, which may compel landing at an en-route airfield. This problem is unlikely to be as severe with Concorde's successor because it is probable that it will be able to operate almost as efficiently subsonic as supersonic. All this creates problems in the present air traffic environment, and emphasises the need for new thinking on air traffic management and flight deck displays so that the introduction of large numbers of high-speed civil transports (HSCT) can be accommodated.

7-4 The preceding paragraphs give some idea of the specific problems associated with the operation of a SST; it is not comprehensive, but serves as a background to the factors that need to be considered in the development of a flight deck for a second generation SST.

Operational considerations

7-5 HUD are likely to be the primary means of displaying information during the critical stages of flight, integrated with a three-dimensional synthetic vision display of the terrain supported by imaging sensors fused with graphics overlay for precise guidance and situation awareness. This "head up" flight deck would present all the vital information needed in one place — on the windscreen. It is probable that flightpath information would be in the form of a pictorial "pathway in the sky", as it has been demonstrated that this provides substantially increased spatial awareness. This whole integrated concept is critical to the safe operation of a complex aircraft such as the HSCT with only a two pilot crew. A head-down display would be available for en-route use when workload was low. Standby instrumentation would remain a requirement; it could either be in the form of a current generation "head down" display, or be presented on the screen as a HUD. The latter option would appear desirable since it conforms to the philosophy of keeping the pilots' eyes in one position.

7-6 The navigation display must take into account the possibility of descent to subsonic cruise levels safely in the event of a critical problem; with certain failures the aeroplane will have to descend regardless of ATC clearance having been obtained. In Concorde, the pilots have more time to deal with communications and navigation because the flight engineer takes on a significant share of the total workload. With a two crew aircraft it will be imperative that the navigation display shows not only the position of the aircraft itself, but also the position of all other aircraft within a defined range. This display would provide a picture of all potential conflicts

in the event of an enforced descent to subsonic levels. The navigation display should also show potential infringement of boom-protected areas as well as the essential function of weather radar.
7-7 The solution to these requirements may be seen in Chapter 6, Future Technology, in the form of a satellite navigation system enhanced by a digital database. This would allow orientation and display of boom-protected areas, airspace boundaries, and over water navigation background such as lines of latitude and longitude. The problem of enforced descent following a technical problem necessitates the philosophy of an autonomous aircraft, and the digital database with a development of TCAS included must be the solution to the en-route operational needs. The management of the flight would only be practical using knowledge based systems or artificial intelligence; indeed, such systems would seem to offer the ideal solution to in-flight problems during supersonic operation in a two-crew aircraft.
7-8 A clear display of the aircraft's actual centre of gravity, as well as the fore and aft limits throughout the speed range would be essential, perhaps shown on the HUD. In the absence of a flight engineer, fuel transfer during acceleration and deceleration would be an automatic function; potential C.G. limit infringements should be clearly displayed, with a simple manual override of the system should the automatic fuel transfer malfunction. Total air temperature must also be clearly displayed at all times. Whether the HSCT will have a movable nose section is not certain but natural vision will probably be restricted anyway. The use of such features as wide-angle cameras for taxiing will not eliminate the need for direct vision through a side window to be available to the pilot.
7-9 Bearing in mind the intense workload that exists in some emergency and abnormal situations (particularly an enforced descent from supersonic cruise) and in the absence of a flight engineer, any successor to Concorde will have to be automated to a very high degree. The involvement of the pilot in the operation will need careful thought bearing in mind the need for human centred automation. There will always be times when the human becomes involved in the solution of a problem, and operating techniques and design parameters must always allow that to be possible.

8. CONCLUSION

This Paper was conceived from the misgivings of pilots from all sectors of the commercial aviation industry over the apparent lack of consultation with them on the development of flightdecks and the associated equipment. It was felt that often equipment was installed without sufficient consideration for how it would be operated, whether the average pilot would be capable of operating it, or whether it was desirable or necessary.
The various points discussed have sought to highlight the problems encountered with some of the latest installed equipment and to suggest ways that they could be overcome. It is recognised that modern technology is capable of taking over the role of the pilot but this will not happen for many decades to come. Instead, this technology should be channelled into developing fully autonomous aircraft with the capability of operating anywhere in the world, and simplifying pilots' tasks without excluding them from the operational loop.
It is therefore essential that pilots who are to operate future aircraft are included in the consultative process and development of these aircraft.

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