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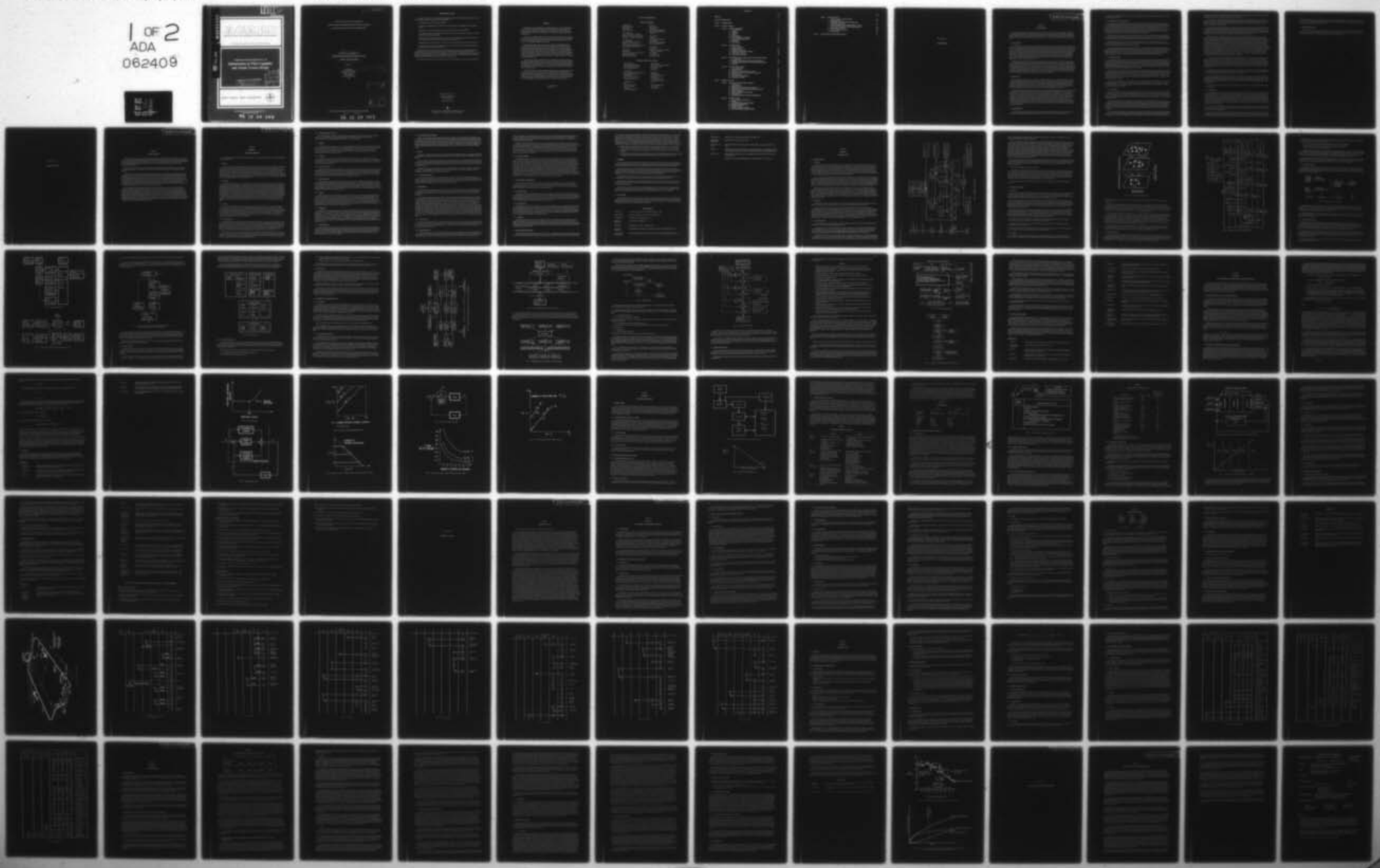

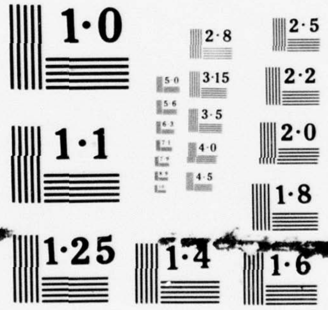
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AGARD

ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

7 RUE ANCELLE 92200 NEUILLY SUR SEINE FRANCE

AGARD ADVISORY REPORT No. 118

Optimisation of Pilot Capability and Avionic System Design

DISTRIBUTION STATEMENT A
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⑭ AGARD-AR-118

NORTH ATLANTIC TREATY ORGANIZATION

ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

⑨ AGARD Advisory Report No.118

⑥ OPTIMISATION OF PILOT CAPABILITY AND AVIONIC SYSTEM DESIGN.

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⑪ Nov 78 ⑫ 98p.

This Report was sponsored by the Avionics Panel of AGARD.

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Published November 1978

ISBN 92-835-1292-8

Set and printed by Technical Editing and Reproduction Ltd
Harford House, 7–9 Charlotte St, London, W1P 1HD

PREFACE

Working Group 08 was initiated by the AGARD Avionics Panel in 1976. The objective of the Group was to prepare a joint report which would guide future combat aircraft and system designers to achieve a better blend of aircrew and machine. The task included the examination of general areas which would appear to require further research and to identify particular topics.

The study was completed in March 1978 and included contributions from mainly three NATO nations, the Netherlands, the United States and the United Kingdom, and contributions from several co-authors and consultants who helped the prime authors in their task. Their efforts are acknowledged and gratefully appreciated.

The study was unusual in that the team included members of the Flight Mechanics, Aerospace Medical, Guidance and Control, and Avionics Panels. The resultant mixture of technical expertise and disciplines provided some natural differences of approach towards detailed subjects and it produced various styles of presentation. Some editorial collation was necessary but, hopefully, the specialist views and styles have not been lost in the attempt to publish a coherent paper. Introductory material and concluding recommendations should give the general interest reader a guide to the collected views of the Group and to the research programmes suggested. More detailed text is available in the body of the paper for the working level or desk level specialists.

There was a common and strongly held view by the Working Group that the study and its findings should play a significant part in convincing operational staffs and design teams that they should give serious attention to the subject under review, which is believed not to have been addressed in a scientific manner so far. The possible goal of cheaper total aircraft systems, at least as efficient, if not more so than current equipment, deserves support by all members of the NATO community.

The final editorial process required substantial modifications to original draft submissions by the authors to ensure a continuity of style, a consistent approach to the subject and reduction of subjective opinion. This process could continue for only a limited period and it was necessary to conclude the refinement at a reasonable time. Some contentious items which would have required a considerable further amount of editorial work were omitted therefore. The editor apologises to any author whose work may have been affected in this way.

F.S.STRINGER
Editor

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INTRODUCTION

Section 1

INTRODUCTION

The purpose of this book is to stimulate the interest and awareness of aircraft and system designers to ensure that the real man/machine interfaces are tackled properly and in an ordered fashion to provide a better blend of human and machine capability and to give a more effective total weapon system for each mission type. Reduction of workload is not the main criterion since useful employment of military aircrew can require a concentration of effort for most of each sortie.

1.1 BACKGROUND

A considerable increase in complexity of the modern military aircraft over its ancestors of, say, World War II is very evident. Two inter-related reasons for this may be distinguished, without attempting to decide which is 'cause' and which is 'effect'. On the one hand, technology development, in all its application, provides the capability for increasing performance and potential effectiveness. On the other, the operational requirement has steadily increased, not only in terms of speed, range, and payload, but also for the conduct of missions in increasingly more difficult or hostile situations and environments. Throughout all of this development, one part of the system, namely the crew, has remained constant. The crew are no stronger, cleverer or more responsive than they ever were. Training methods have, of course, been adjusted to develop the necessary skills needed to operate the modern more complex systems, but the fundamental human limitations are the same and will remain so.

The proposal which led to the formation of the Working Group (in November 1975) argued that modern military aircraft, both fixed and rotary-winged, embody very sophisticated and expensive avionic equipment to enable them to meet increasingly demanding operational requirements. The aircrew are required to perform tasks which require considerable skill and which tend to produce a very high workload. At present therefore, efforts are made to automate some of the equipment operations in order to relieve the workload. The result is costly equipment development, high capital cost and expensive support requirements. The method of "reducing the workload" associated with individual equipment is often performed without regard to the integration of the crew tasks; it can eventually even bring about an unacceptably high overall workload and often fails to take advantage of the aircrew capabilities.

1.2 OBJECTIVES

The main objectives of this book are to curb the continued development of more sophisticated equipment which disregards the human factors, to examine the aircrew potential, and to suggest how the latter could be better exploited to satisfy the operational requirements. Therefore firstly the crew capabilities and limitations should be examined, and then methods devised to match the system to these capabilities. Training methods that will best exploit aircrew capabilities must follow. The objective however is not to save money by making the crew work even harder, but to suggest how continuing effort can make the best use of this important human element of the system.

There are difficulties in defining the aircrew in terms of absolute capabilities and limitations. Any one sample of the pilot population is a variable quantity, with wide variations of performance in different situations – particularly in the military sphere. The best of studies and assessments in peace time may give only a little guide as to what might be expected in war. It appears that the success rates of combat pilots have shown that only one or two members of any squadron are responsible for most of the kills. It would be useful to quantify the differences between pilots so that the equipment can be matched to give the maximum benefit. Designers cannot wait for such a final definition of crew capabilities but that should not prevent the start of applied research. The technology and the mission requirements advance hand-in-hand, and decisions must be made in the process of specifying and procuring military hardware with a conscious understanding of the aircrew problems. Consideration should be given to the overall and consequent effects upon the weapon system.

1.3 METHODOLOGY

For the present it appears prudent to examine the subject and suggest areas of research to ensure that the crew potential is investigated so that complexity limits may be set and the cost of avionic systems thus reduced.

In this work the overriding factor is to increase the overall capability of the total system rather than achieve a direct reduction in crew workload.

1.3.1 The Development of Avionic Systems

For a long period after World War II, two factors, the capability and the requirement, kept easily and naturally in step. Technology advances, like jet propulsion, powered flying controls, supersonic performance, guided weapons and so on provided new capabilities that were quickly and unquestionably translated into new requirements. In parallel with these examples, which primarily affected the performance of the aircraft – in the classical engineering sense – as a military weapon, came a succession of others which more directly affected the pilot's performance as a system controller – autopilots, auto-stabilisers, navigation and attack systems, target acquisition and aiming systems and so on. These primarily aided the pilot to use the aircraft and its performance more effectively.

Up to some stage in the development of this latter series of what we now recognise as avionic systems (as opposed to airframe, engine and weapons systems) their translation into firm requirements was also accepted without question. The technology existed, the overall system capability was improved, and, despite the extra cost, it was all worth having.

Without suggesting whether or not the airframe/engine/weapon aspects have reached or passed that stage, the Working Group had to consider whether, in terms of avionics, we have now entered a stage where the introduction of at least some of this new technology must be seriously questioned.

It seems appropriate here to attempt some better definition of the elements of the total system which were the subject of the Group's study, rather than simply to refer to them as "avionic systems" We have avoided a digression into philosophical arguments about the way in which an operational requirment should be stated, and have accepted that, typically, an aircraft is required to deliver certain weapons against some specified ground or air target, some specified distance from base, in the face of enemy opposition and of natural hazards such as the weather and terrain.

1.3.2 Man-Machine Systems

The design team produced initial proposals for basic airframe/engine configuration which will meet the pure performance requirements; the aircraft will have the speed, range and payload capability to do the specified job, operating from specified bases. The capabilities of the human pilot will not yet have been considered, though his physical limitations naturally do influence these basic proposals. The pilot requires a cockpit of adequate size with a habitable environment, and if extreme manoeuvrability has been specified, or if there is some "a priori" advantage in reducing the physical size of the aircraft, the reclining or semi-reclining seat may be proposed.

Up to this point, only the basic physical characteristics of the pilot will have influenced the design, but then comes the question of what additional equipment must be fitted because he has only a limited functional capability. He cannot navigate to his target and return to his base unaided except in good visibility and over short distances. He cannot detect or select targets until he can see them, nor can he recognise when he is being attacked until too late. He cannot aim his weapons except in the crude sense. He cannot communicate with the ground or with other aircraft. In short, he needs a lot of assistance from "avionics".

So far, there is still no problem. The technology to meet these needs exists or can be developed and, at a cost, the necessary equipment can be provided and installed. Space and weight penalties have been greatly reduced by modern technology and there is no fundamental "physical" reason why every aid should not be given to the pilot – until we ask whether the pilot can use them all.

1.3.3 Pilot Workload

Thus, we now come to the crucial issue of pilot workload. We do not need a precise definition of "pilot workload" to recognise that any pilot, no matter how highly-skilled or well-trained, can be overloaded if he is expected to do too much. A navigation system for example, may be capable of extreme precision or it may offer facilities unheard of a few years ago, but it will be useless if it needs the pilot's attention when he is busy on other vital tasks – or if it is extremely difficult to operate.

The obvious solution seems to be automation, which can reduce the pilot workload to some extent; but even if the operation of the device is entirely automatic, the pilot generally needs some assurance that it is functioning properly; he still needs to "manage" it as part of his total task, and it still demands some of his attention, some of the time. If the device is expensive in first cost and in maintenance effort, the question will be asked whether it is worth fitting at all; what sort of a job could the pilot do if it were omitted, or replaced with something much simpler, though of less capability.

Such questioning ought, logically, to be applied to every system incorporated in the aircraft. There is little doubt that such questions are often asked by pilots and maintenance engineers during the early development flying and initial operational use of a new aircraft. By that time, expensive mistakes have sometimes been made, and though these may be rectified by modification or design improvements, it would obviously be better if they were avoided by more careful consideration of the pilot's capabilities and limitations in the first place.

This is the question which the Working Group has attempted to answer. It may be possible, by a more rational assessment of the human operator's fundamental capability and the extent to which this can be improved or developed by training to apply a more scientific approach to man/machine interaction problems and hence to move nearer to the optimum combination in the design stage.

Consideration of fundamental requirements and optional extras for the human pilot is often contentious. No equipment designer will relish the suggestion that his component part of the system is an unnecessary luxury. It is a basic concept that some parts of the total system are vital to the pilot's ability to fly and control the aircraft while others make it possible for him to perform missions he could not otherwise do. Absence of such parts may degrade the man/machine capability but may not make every mission impossible or necessarily endanger the aircraft.

A classic and obvious example of the first category is the primary powered flight control system. To meet the requirements for minimum acceptable flying qualities, a stability augmentation system (SAS) is generally mandatory. Where exploitation of active control technology (ACT) confers a necessary performance advantage (relaxed static stability, or manoeuvre load limitation, for example) further complexity in control system design is inevitable. Engine controls, fuel management systems and so on are further examples of fundamentally vital systems which must be incorporated and which must function properly at all times. This leads to the simple definition of systems which necessarily create some degree of pilot workload because they must be monitored or managed or otherwise attended to from time to time, but they must be included in the basic list of essential equipment. All items in this list would, by their failure or deletion, endanger the aircraft immediately or in a very short time, even on the simplest of missions. All must function throughout every flight, and their management or control should be automated so as to minimise their contribution to the pilot's workload. Ideally, all should be 100% reliable and need no attention. In practice, acceptable reliability is usually achieved via redundancy, and the pilot needs to be aware of the status of each of these vital systems. They cannot be omitted, so they must be made as simple, safe and reliable as possible.

The remainder of the systems with which the pilot has to work require some justification for their presence in the aircraft, at the proposed level of cost, complexity and consequential workload. In the probably rare event that the aircraft/pilot combination can perform operationally useful missions without it, the offending equipment can be simply deleted. More generally, the question is whether some alternative means can be found to provide most of the original capability in a cheaper, simpler and/or easier-to-operate form. This may mean a search for an alternative piece of hardware, but it should include a study of alternative ways of flying the mission so that the requirement for the equipment may be relaxed.

In the following chapters, the operating environment for the pilot of the air combat and the strike attack fixed-wing aircraft, and the typical military helicopter are described. The variety and complexity of systems and equipments that are, or could be provided to assist the pilot in his task are readily apparent.

Some of these systems or equipments can be referred to as "optional extras" in precisely the same sense that an automobile main headlights are an operational extra; the vehicle can operate in daylight without them, but its capability rapidly diminishes as the light fades. By contrast, the vehicle braking system is fundamentally vital to its safety. The problem being addressed is how to justify the cost of these "extras", so that the decision to include them may be made on a rational basis.

Inevitably, no simple rule-of thumb emerges. Nevertheless, some suggestions for further studies are offered at the end of the Report.

1.3.4 Digital Systems

The digital computer has revolutionised the design of avionics systems for air combat aircraft. An advance which is having a profound effect on avionics system design is the development of the microprocessor. A single microprocessor barely larger than a paper clip can contain several thousand transistors, equivalent to a large rack of instruments just a decade ago. It acts as the central arithmetic processing unit and when integrated with a solid-state memory and input/output peripherals, becomes a microcomputer. Because of their low cost, compactness and reliability, microcomputers are expected to revolutionise a variety of functions in missiles and aircraft[10] Low cost and reliability are important and the latter may be translated as low cost because of maintenance reduction. Digital systems also contribute to lower life cycle cost due to ease of retrofit.

It is claimed that digital systems offer the possibility of reduced component replacement cost. This claim is based upon the premise that costs will include software which is easier to adjust than hardware. Some recent experience shows this premise to be of doubtful origin.

Digital avionics systems are of complex design but they require less maintenance than their analogue counterparts. Programmes can be developed which continually check the health of the system. By means of the self-checking capability the avionics component which fails can be identified, down to a certain level, while still airborne. After the aircraft lands, digital aerospace ground equipment (AGE) can isolate the failed component at a more detailed level. Through such software routines fault finding can be made easier since faults can be isolated quickly. The avionics therefore become a more cost effective aspect of the aircraft life cycle.

1.4 REPORT STRUCTURE

Following this introductory section, the Report is divided into three further sections. Section 2 deals with human factors aspects in the system design context. Section 3 considers the workload for specific aircraft roles and Section 4 presents the Working Party conclusions and recommendations for further research.

SECTION 2

HUMAN FACTORS

Section 2

HUMAN FACTORS

This Section contains four chapters and begins with a Chapter describing relevant human capabilities. The descriptions cover sensory characteristics such as sight, sound and touch, and mention various other aspects including kinesthesis, sensory capacity, signal detection, monitoring, processing and decision making capabilities. Display-control relationships and Stimulus-response compatibility are also discussed. The first chapter finishes with a description of human psychomotor characteristics.

The second chapter in this section describes a system design methodology and illustrates the role of workload management in this context. Some effort has been made by succeeding authors to refer to this methodology in their own texts.

The third chapter deals with the modelling of aircrew performance by quantifying human capabilities into systems engineering terms. It is a basic tenet of human operator modelling that a pilot is an information processor-controller comprising an element in a control loop. The aim of this approach is to mathematically describe the operator so that a man-in-the-loop engineering analysis can be performed on the aircraft with a human pilot in place. The limitations of two widely used human operator models are discussed, these control-theoretic models are considered unsuitable for workload modelling. A less widely known model, based on information theory techniques is introduced and a worked example provided. This model should provide a natural context for quantifying pilot workload, designing optimum cockpit displays, and configuring avionic systems under workload constraints.

In the fourth and final chapter of this section, the concept of reducing the avionic costs of future aircraft by decreasing the reliance on equipment and increasing the responsibilities of the pilot is examined from the aspect of training. The author postulates that as part of the task allocation process, there needs to be a thorough analysis of the pilot's tasks and consideration given to alternative ways of accomplishing the missions of the weapon system with man-machine support. There also needs to be an analysis of which tasks can be accomplished more efficiently by man or by machine. Because of man's adaptability and versatility, it is difficult to set any precise limits to his capacity to receive and process data and execute the indicated actions. His capability can be enhanced to some degree however by extending training. The chapter goes on to discuss advances in capabilities of part-task trainers and simulators and concludes with considerations of the training of maintenance personnel.

Section 2

CHAPTER 1

HUMAN CAPABILITIES

This chapter provides a brief description of man's capabilities. A bibliography is provided to allow more detailed study of specific aspects.

1.1 VISION

It is estimated that 80% of flight information is visually acquired. Typically, a man can discriminate on an absolute basis 10 colors, 5 sizes of figures, 5 brightnesses of light, and 2 flicker rates, when viewing each separately and non-sequentially under favorable conditions. He can read 6-point type with 30 foot lamberts (ftL) of light; has a visual form field of about 130° vertically and 208° horizontally, with maximum acuity at the center; requires about 0.6 sec to change fixation from near to far; and takes about 30 min to completely adapt from daylight brightness to darkness. He suffers discomfort and impaired vision if bright lights or reflections are located within 60° of his line of sight; and suffers loss of visual acuity as speed of movement of objects increases; e.g. for angular velocity of 50° per second, acuity is 57% of normal; for angular velocity of 150° per second, it is 19%.

1.1.1 Sensitivity

The human eye is sensitive to only a relatively narrow band of electromagnetic radiations, (approximately 400–700 *nanometres*). The daylight adapted eye is most sensitive to energy in the yellow-green region around 555 nanometres. The dark-adapted eye is most sensitive at about 507 nanometres which is in the green part of the spectrum. Light sensitivity at a given moment is dependent on a number of factors: the time that the eye has been exposed to a certain level of illumination; individual characteristics such as age; the region of the retina stimulated; the nature of the stimulus, such as the duration, wavelength, composition, and intensity of light; and the physiological and psychological condition of the individual. A light of low intensity may be clearly seen against a dark background. To be seen against a bright background, however, the light must have much higher intensity. Visibility of light also depends upon area (visual angle) of the light surface being observed. Greatest sensitivity of the retina in darkness has been found to be about 40° from the point of maximum acuity under daylight viewing conditions (fovea) on the nasal side of the eye and about 20° from the fovea on the temporal side. More intense light is necessary to perceive short flashes of light than for longer flashes.

1.1.2 Acuity

Visual acuity is the ability of the eye to perceive fine details. The discrimination of 1 minute of visual angle is considered normal. Visual acuity is a function of background luminance, duration of exposure, luminance contrast between the object and its background, retinal location, and color of illumination. Visual acuity 'decreases' progressively as the magnitude of the acceleration force on the observer increases with the acuity threshold at 7'g' being twice that at 1'g'. Acceleration has a significant and progressively limiting effect on the threshold at all levels. For example, at a luminance of 0.01 mL, the minimum angle increases from 4.0 min of arc at 1'g' to 7.59 min at 4'g'; at 150 mL, the change in visual angle is 0.25 min of arc from 1'g' to 4'g'.

1.1.3 The Visual Field

The visual field may be defined as that part of space that can be seen when the head and eyes are motionless. The monocular field (for one-eyed vision) is limited by (1) the refractive power and physical arrangment of the cornea, lens, and retina, and (2) the nose, cheeks, and other facial structures. It varies from some 104° from the line of sight on the temporal side to some 60° to 70° on the nasal side. The monocular fields of the two eyes overlap to form a binocular field. The visual field can be extended by eye, head, or body movement through 360° in all planes. When the eyes rotate, vision is extended beyond 104° from straight ahead, where facial contours do not get in the way.

The horizontal field of each eye alone is approximately 166°, and for both eyes fixated on a point straight ahead, about 208°. Colour is perceived in the area of overlap extending for 62° on either side of the fixation point. The vertical visual field is approximately 130°, with colour perception occurring from 30° above to 40° below the horizontal line of vision. The field view of colour is not the same for all colours.

1.1.4 Other Characteristics of Vision

Other characteristics of human vision which have been investigated and for which data are available include his ability to (1) perceive depth, (2) judge changes in brightness, (3) estimate distances, (4) discriminate form, (5) discriminate colour (6) adapt to changes in brightness, and (7) detect movement.

1.2 AUDITION

The auditory channel accounts for 10–15% of acquired flight information. Hearing is the phenomenon of sensing pressure fluctuations from some vibrating source. Auditory sensations are experienced when acoustic energy sets off a series of mechanical, neural, and central nervous system (CNS) events in an organism. Sound waves may vary in frequency, amplitude, and complexity. What a man perceives does not bear a linear relationship to the physical dimensions of the sound waves entering the ear.

1.2.1 Sensitivity

The minimum intensity to which the ear responds varies as much as 80 dB or more, depending on frequency. Throughout the area of greatest sensitivity (2000 to 3000 Hz), the ear responds to sound pressure as low as 1/3,000,000 gm. Prolonged exposure to high-intensity sound (85 dB or more) can result in the diminishing of the ear's sensitivity, especially to the higher frequencies.

1.2.2 Subjective Measures

Frequency and intensity are physical properties of sound which can be measured physically. Perception of loudness and pitch is subjective and must be measured by means of subjective scales. Units of measurement for loudness are the phon and the sone, and for pitch, the mel. Intensity is correlated with loudness, but the correlations are not invariate. For a given intensity, loudness is greater in the middle of the frequency scale than at the upper or lower ends. Pitch is correlated with frequency, but at certain frequencies it varies slightly with intensity.

1.2.3 Speech Perception

Communication among system personnel is usually by means of speech. Average speech at a distance of 1 metre corresponds roughly to sound falling in an intensity range between 60 and 75 dB. The speech spectrum of the normal voice lies almost entirely within the frequency range from 100 to 8000 Hz. Spectral analysis of speech over a period of time indicates that over half the energy is expended in frequencies below 1000 Hz. When noise is present, speech may be masked making interpretation of the sounds by the listener difficult or impossible. As the spoken material becomes more familiar to the listener, less masking of speech occurs.

1.2.4 Masking

Almost every auditory communications system contains unwanted sounds which raise the hearing threshold and decrease the intelligibility of the sound or signal. Masking is the process whereby the threshold of audibility for one sound is raised by the presence of another (masking) sound. The amount of masking is customarily specified as the number of decibels the threshold is raised because of the masking sound. A sound is more effective in masking a sound higher in frequency than itself than in masking a sound lower in frequency than itself. Masking is greatest when the masking frequency is close to the signal frequency and decreases as the separation between the two becomes greater. The masking effect increases as the intensity of the masking tone rises.

1.2.5 Intelligibility

Intelligibility is the psychological process of understanding meaningful words, phrases, and sentences which may occur face-to-face or over communication systems. Speech intensity levels greater than 40 dB are required for optimum intelligibility. At a level of 85 dB, speech is noticeably (subjectively) loud. Above 100 dB intelligibility decreases due to distortion of the ear. The ratio of speech level to noise level (S/N ratio) grossly affects intelligibility. For satisfactory communication of most voice messages in noise (75% intelligibility), the speech level should exceed the noise level by at least 6 dB. The use of hearing protection (earplugs or earmuffs) increases intelligibility in noise levels ranging from 85 dB to above 100 dB. A single voice may be discriminated from among two or three simultaneous voices but not from among four or more.

1.2.6 Articulation Index

The articulation index (AI) is a measure of the percentage of test words which can be transmitted correctly over a communication channel. If speech is distorted by passing it through a high or low-pass filter or a frequency-restricted microphone, the AI changes. Amplitude distortion or peak clipping to conserve available transmitter power does not reduce the AI below 70%. Speech can be distorted in frequency, amplitude, or phase, or masked by noise, but the listener may still be able to interpret the message.

1.2.7 Other Characteristics of Hearing

Ability to locate sound sources is dependent primarily upon binaural cues, such as differences in loudness, in time of arrival, in sound composition, and for some sounds, in phase. Hearing acuity varies greatly among individuals; within a normal group, it may vary as much as 20 dB or more, and an individual's acuity may vary 5 dB or more within a short period of time. There are also differences in hearing levels due to age, sex, and past exposure to loud noises. Sound may influence performance and contribute to boredom, fatigue, or relaxation, depending on the type of task. High-frequency noise and irregularly variable sounds are more annoying than low-frequency and continuous or periodically changing sounds.

1.3 TOUCH

The surface of the body (the skin) is also used by the pilot to obtain flight information. The skin has many different sensory functions – mediation of touch, vibration, temperature, and pain. Therefore a variety of messages can be sent to the brain.

Touch or pressure is experienced when a gradient is formed upon the skin by some mechanical stimulus, whether the direction of force is outward or inward. Pressure sensation remains as long as the rate of movement into or out from the skin continues. The time required for adaptation to pressure increases with the pressure exerted and varies inversely with the area stimulated.

Sensitivity to vibration is not a separate sense, but is primarily dependent upon pressure sensitivity. The sensation results when a mechanical stimulus oscillates continuously. Human beings can feel as little as 0.00004 inch double amplitude of vibration at frequencies between 100 and 500 Hz.

1.3.1 Tactile Communication

Tactile communication represents a possible but limited channel of information transmission when visual and auditory channels are overloaded. The use of cutaneous stimulation (e.g. mechanical or electrical) for emergency warning purposes and guidance seems feasible. Cutaneous stimuli are received and responded to as quickly as auditory, and may be more attention-demanding, especially if a mild degree of pain is elicited.

1.4 KINESTHESIS

The primary source of information about the movement and position of the parts of his body is kinesthesis, or the muscle sense. One of the main functions of the kinesthetic sense is to enable a human being to control his voluntary muscular activities without the aid of vision. Secondly, the system serves the perception of changes in orientation and equilibrium.

In executing movements without the aid of vision, the individual must depend on the kinesthetic sense as a guide. This is most relevant to piloting in executing activities where the visual system is diverted elsewhere. Where movements are restricted (e.g. where paths of movement are controlled by grooves), there is a tendency to overshoot at short distances and fall short at long distances, except in vertical top-to-bottom movement, when the goal is overshot for all distances. In free blind positioning (reaching for a target or control), the greatest accuracy is shown in dead-ahead positions at the lower level and the least in side positions at the upper level. Preferred-hand targets can be reached more accurately than nonpreferred, and practice reduces the magnitude of errors. One-handed movements inward or outward are slightly faster than lateral movements, and for a right-handed operator using the right hand, right-to-left lateral movements are faster than left-to-right. When in-out positioning movements are required, better performance is obtained when the distances are reasonably short and when angles of movement are to the right of the right-handed worker, somewhere around 60°. When two-handed simultaneous positioning movements are made, the speed is optimum when they are at angles of about 30° from the straight-ahead direction, while accuracy is greatest when they are performed at 0° (straight ahead).

1.4.1 Control Forces

Forces exerted by the operator on a control and the opposing force of the control itself provide a substantial part of the proprioceptive information used by the operator. The degree to which such forces are capable of discrimination over a wide range of movement is an important limiting factor, along with such others as strength, speed, and fatigue, to the efficiency of operation of any control.

1.4.2 Spatial Orientation

In the natural environment, the individual maintains his orientation and equilibrium by use of a combination of the visual, auditory, kinesthetic, skin, and inner ear sense modalities. While man normally depends upon all these senses to help him remain on a reasonably even keel, compensation can be made to some degree for the deficiency of one or another. Abnormal or conflicting conditions make discriminations more difficult and sometimes cause serious errors of perception. Maintenance of the visual environment is extreme under such conditions in flight. An individual can accurately judge vertically when the framework of the visual field is aligned with gravitational forces acting upon the receptors in the semi-circular canals.

Perception of the vertical (the direction of action of normal gravitational forces) and of one's postural relation to that vertical are important aspects of orientation. Both visual and postural vertical are largely determined by joint action of visual and gravitational forces. The average threshold for body tilt with postural cues alone has been found to be between 2° and 3°, with that of backward tilt about 0.5° higher than for other quadrants. Elimination of visual cues raises these thresholds, so that tilts of 10° to 15° may not be recognized. Where visual cues are purposely distorted, subjects tend to base their judgments on what they see rather than on how they feel, even though these judgments are completely at odds with the real situation.

1.4.3 Orientation in Flight

The pilot of an aircraft or space vehicle needs to be oriented to his craft and to the earth, and possibly to other vehicles. Typically he will have no trouble perceiving how he is lined up with his own craft. The most compelling cues are those from the visual frame of reference of the interior of the craft, reinforced by 'postural' information from the semi-circular canals. In flight this system is affected by acceleration as well as by gravitational forces. When visual and postural cues conflict, visual cues usually predominate. If the pilot does not have visual cues, he must depend on instruments and his own "sense" of the vertical. Judgments in the lateral plane (roll) are more accurate than those in the medial plane (pitch). There is a delay of approximately 7.5 sec before tilt is felt and adaptation causes the feeling of tilt to disappear before one is level again, causing problems in orientation. When facing forward the person experiences a feeling of backward tilt (climbing) under linear acceleration, and a feeling of forward tilt (diving) under deceleration; when facing to the left, he feels tilted to the left under acceleration and to the right under deceleration. With angular and radial acceleration, tilt is grossly underestimated and perception lags. Recovery from turns is interpreted as a turn in the opposite direction. Visual and gravitational cues may conflict, producing "pilot's vertigo".

1.5 DATA-SENSING CAPABILITIES

The role of the human being in the system is to detect information regarding some aspect of his environment, process this information in some manner, and transmit it in whole or in part to some response agency which affects appropriate adjustments in the environment. Thus, the ultimate performance of the system is related intimately to the ability of the operator to detect and process relevant input information.

1.5.1 Distorting Factors

When it is possible to reduce distortion on some, but not all, display channels, the greatest benefit seems to result from optimizing those displaying input information. Distortion of feedback information is less serious, due to the redundancy afforded by kinesthetic cues. The distortions created by system lags can be averted in many systems by displaying feedback information not only of system output, but also of its derivatives. This technique, called "quickening", can reduce the effects of lag and can also greatly simplify the operator's task.

1.5.2 Signal Detection

Human performance is limited with regard to excessive temporal demands (e.g., rapid sequential events, overlapping signals, multichannel events, etc.), and also with respect to infrequent input occurrences. In general, performance in monitoring extremely low-frequency events deteriorates over time, and a number of relevant variables have been identified. Among the most prominent are (1) signal characteristics: frequency, regularity, size, intensity, and spatial distribution; and (2) task variables: spacing of rest periods, level of extraneous noise (visual and auditory), presence of other stimuli, and schedule of reinforcement for observing responses.

1.5.3 Monitoring

Although a man may report a fair number of signals correctly, his performance tends to deteriorate as the watch progresses. However, if he does report a signal, he usually does so with only a slightly longer delay than when he is highly alert. The human operator should not be assigned monitoring tasks that require continuous attention to a display unless absolutely necessary. Such jobs should be done by machines, and man's role should be limited to judgments about the signals reported by the machine.

1.6 THE TRANSFER FUNCTION

Feedback-control theory has provided a powerful new tool for the understanding of how the human operator carries out the perceptual processing of input information in closed-loop control tasks. The tool, called the "transfer function", is an equation for linear systems which spells out the relation between sensory input and motor input. On the practical side, it enables the design engineer to anticipate the capacities and limitations of the human being so as to augment or supplement the characteristics with machine aids. On the theoretical side, the work on transfer functions is of great significance, for it details the kind of perceptual activity required to attain skilled levels of performance in complex control systems. It has been established that the particular operations employed by the man are dependent upon input characteristics (frequency), input mode (compensatory vs pursuit displays), control dynamics (simple proportional control through complex aircraft dynamics have been used), and the level of training. In general, it has been found that:

(a) Man will estimate and weigh the higher derivatives of the input signal if required to do so, as in controlling through higher order dynamics or, if the availability of such information is high, as in the pursuit display.

(b) There appears to be a regular systematic progression from lower to higher orders of control as a function of training.

(c) As task-induced stress (increased input frequency) is introduced, the man generally reduces the weight assigned to higher derivatives of the input signal, and in this sense regresses toward a lower order of control.

1.7 SUMMARY

80% of the pilot's flight information is acquired visually. Though there are limits to man's acuity and thresholds, the spectrum of detectable energy, range of encoding possibilities, and capacity for multiple inputs far exceed that of any other information channel. The visual channel is reasonably resistant to noise in the typical cockpit environment.

Most of the remaining 20% of the pilot's flight information is acquired auditorily. Speech is a principal mode. Audition is moderately susceptible to noise and requires moderately high energy levels in order to ensure that information is transmitted. While not completely a single channel system, audition is significantly more limited than vision to multiple inputs. It does however display some virtuosity with regard to encoding options.

Kinesthesis/spatial orientation account for a minimal amount of the pilot's flight information, largely in terms of a background flow of relatively gross data which remain unobtrusive until it deviates from the expected.

Data processing capabilities are the significant arena of pilot overload, being characterized by a narrow range of information capacity. These limitations are considerably augmented, however, by his capacity to predict, extrapolate, and develop unique solutions.

Transfer functions are the classical form of engineering analogues of man. The are limited by a requirement for system linearity and therefore only partly describe man. Optimal control theory is the most recent application in this approach. Its particular advantage is its application to complex plants characterized by a vector of states.

1.8 CONCLUSION

Most of the material presented in this chapter has been the product of extensive experiment. It will be evident to avionic system designers, that the components which will interface with the operator should, where possible, give some recognition of the guidelines offered whether in terms of displays, controls, or instruction sets. To ignore the guidelines must inevitably introduce an operational performance limitation.

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Section 2

CHAPTER 2

SYSTEMS DESIGN

2.1 INTRODUCTION

2.1.1 General

In the introduction to this book a rationale is given questioning the evolution of more highly complex airborne weapon systems. In part, this complexity is in answer to the requirements of the air staff whose operation is beyond the scope of this present work. It may also be attributable to the rather isolated design of each instrument and subsystem. While this may be tolerable for, say, the design of engines, it is certainly disadvantageous in the case of man-machine subsystems (MMS) because for many of these subsystems man is a common factor coordinating and using data relevant to the job in hand. It is reasonable to expect that a greater integration of all data sources and controls, and utilizing more of man's capabilities, may result in a better and more cost-effective product.

Up to now much of this effort mainly was concerned with anthropometric and psychophysical factors, involving the so-called inner loop of flight control. Mission performance however, also depends to a large degree on aircraft capabilities and human functioning which together must meet mission requirements. In this area only little ergonomics research has been done; available data are scattered and seem difficult to apply. The diversity of the pilot's task in different phases of flight or in different phases of the mission introduces many parameters and variables which must simultaneously be dealt with; as a result a very systematic method to analyze the problems in the design of man-machine systems is needed.

Without systematic analysis techniques, the design of the MMS and its operation is very complicated, because technology offers many similar solutions in answer to each partial problem. As a result, design decisions are liable to be taken on a limited number of the possible alternatives open to analysis, and the criteria can sometimes be rather vague. Moreover, in earlier stages of the design the degree of detail is rather coarse, becoming finer as the design nears completion. An undesirable outcome apparent at an intermediate stage must often be traced back to a particular decision at an earlier stage: reiteration is basic to design. Good, or acceptable designs of a product are made because in most cases the evolution is very gradual.

2.1.2 Example

A rather simple example of the proliferation of alternative design proposals or different configurations is given in Figure 2.1 which depicts the process of selection of a defensive system appropriate to a known threat.

In this example there are two methods to realize the required system function, while each method can be implemented by two different means, leading to four different configurations. If existing (commercially available) equipments cannot meet the threat, i.e. their probability of success is lower than required, proposals for an improved design must be requested by the operations requirements branch of the air staff. Thus a new design process is initiated, if significant changes are proposed in one or more aspects, or for new designs, every requirement and constraint, and each function of the man-machine system. Examples such as the control configured vehicle; or a retrofit of all-weather capability would require the systematic revision of the MMS design from the objectives stage onwards.

2.1.3 Top-down Design

Top-down design is, so to speak, starting from scratch; beginning with the objectives and initial requirements and working down towards equipment and operating instructions.

The design process can be eased with the aid of a computer, programmed to generate different configurations or alternative design proposals. It can provide performance versus cost indications at every stage and after each iteration cycle of the design. This can be done when existing design knowledge and experience is augmented by systematic ordering methods and catalogues which list all design alternatives for a particular function of the system.

The initial investment of computer aided design is high; it necessitates the development of a data base and imposes a strict discipline on the structure and processes of the design. Although there remain creative elements, design becomes strictly methodical in those areas where it is required. The rewards come when it proves possible for example to make a

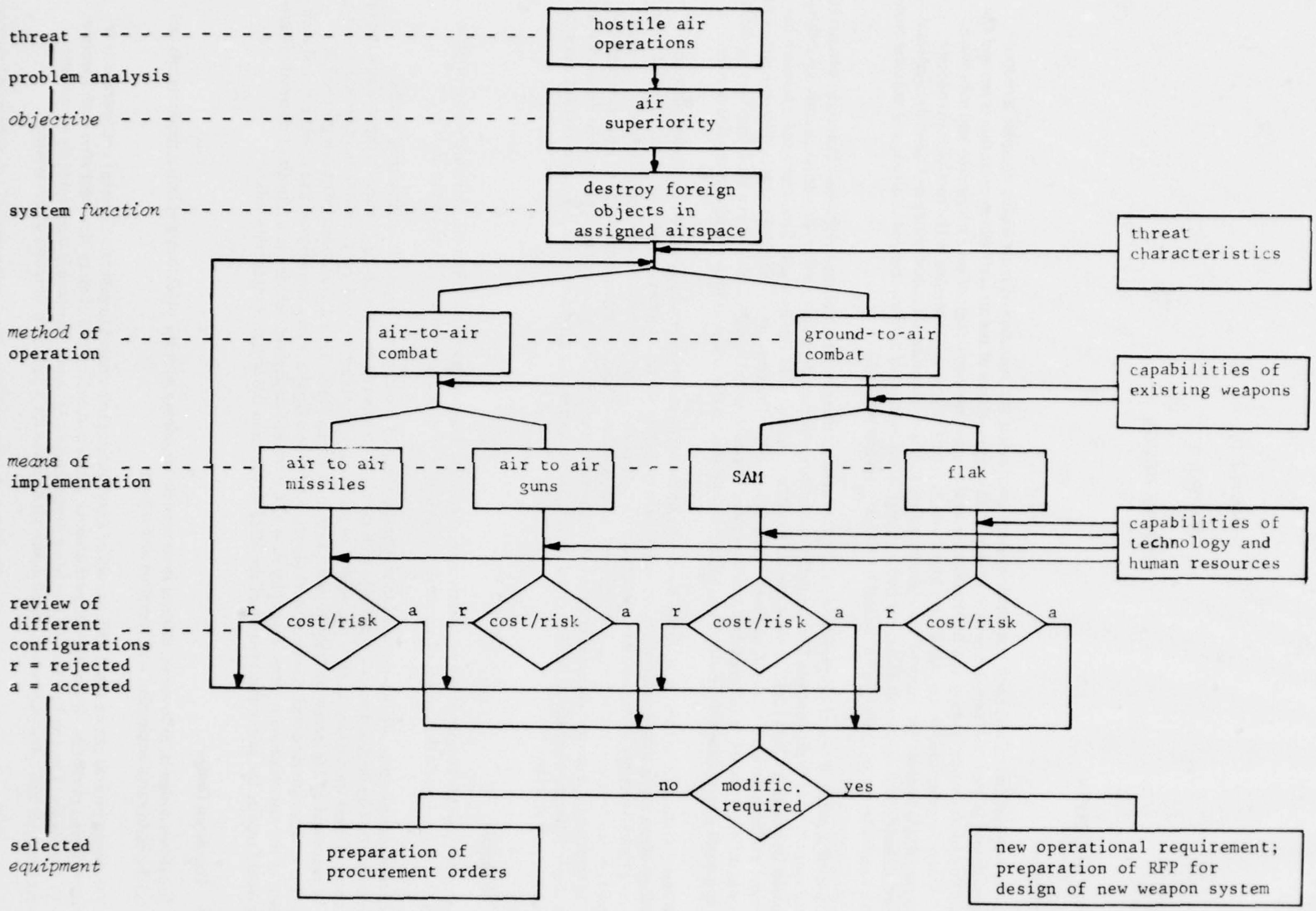

Fig.2.1 Example of selection process

minute by minute analysis of flight procedures to predict possible overload of the pilot, or to determine the effect of cockpit lay-out alternatives on mission performance.

The technical discipline "systems engineering" and the scientific methodology "systems theory" provide methods and means for an orderly, methodical decomposition of systems into their respective components or partial systems down to microscopic detail. These concepts are not new: the use of the term "systems engineering" with roughly its present meaning can be traced to the early 1940's. However, then the concepts of the systems approach were mainly focussed on the time parameter of the engineering design process and its management[1,2] with very primitive treatment of economic and human factors. Systematic design methods remained limited to the breakdown into "phases", for instance: analysis and planning; preliminary design, detailed design and test; production design[3,4]. Recently more insight is being gained into the processes through which engineering design itself progresses[5,6]. To some extent this is due to concepts and analysis methods developed in the science of system theory, which pervades many branches of scientific activity[7] from mathematics to psychology. Thus it is possible to use human factors data, where it exists, orderly and systematically in the design process of engineering systems.

In this chapter it is argued that, in top-down design of aircraft, ergonomists must be part of the design team from the conception phase onwards; and not only for detailed equipment design but, in particular, for activity allocation and task design, to ensure in the early phases matching of equipment characteristics to human functional capability, to control physical and mental load.

The design process itself can be regarded as a system.

Looking back at a particular engineering effort, a complex network of decisions can be identified, pervading every aspect, every function, every subsystem, every component and every task of the MMS. Consequently, the design process can be structured, not only in time but also hierarchically, such that at a higher, coarser detail level, maximum room is provided for alternative methods and means at the level of finer detail. Such a design methodology will be presented in this chapter, and it will be shown that, especially with respect to functional human factors such as task structure the important decisions are taken at the higher hierarchical levels, i.e. in the earlier phases.

In this introduction, the main notions of systems theory and systems engineering as applicable to design will be reviewed.

2.2 SYSTEM STRUCTURES

2.2.1 General

A mission can be segmented into smaller elements, in order to facilitate the identification of the methods and means by which it can be accomplished. Study of the processes carried out in each separate element shows the relations between methods and means in a diagrammatic structure of how the mission is to be accomplished. In complex systems, the diversity and the number of relations is so large that a further breakdown is necessary.

A system has been defined as "a set of objects, together with relationships between the objects and between their attributes"[7]. If one single type of relation is considered, the system can be represented at a structure or network set in a plane which belongs to that specific relation; each node representing one object and each line representing one relation. Such monostructures[8] are quite common: for example, rail maps, genealogical charts or resistance network models of electrical power distribution systems.

Physical reality generally must be described by multistructures which are sets of monostructures with relationships between them as shown in Figure 2.2. Thus, a multistructure is also a system. A subsystem is limited to a specified subset of all objects of the whole system, with all relations existing between them. The subsystem thus is a composite piece, its parts being functionally coherent and operating together to realize the subsystem's main function. Examples which are physically in one piece are: engines, a navigation computer, a tail section.

Examples with functionally coherent parts but physically distributed but integrated with other subsystems are: a power distribution system, a radar altimeter or aerodynamic control surfaces.

A partial system or aspect system contains all objects of the whole system, but only a specified subset of the relations between them. See Figure 2.2.

For example, the total act of navigating the aircraft can be described as an aspect system, encompassing navigation subsystem equipment and the navigation procedures for the particular aircraft.

2.2.2 Activities

Procedures are processes or activities structured in combined or sequential fashion to meet a particular need or specified function in combination with human assistance with or without tools and dedicated equipment. As such,

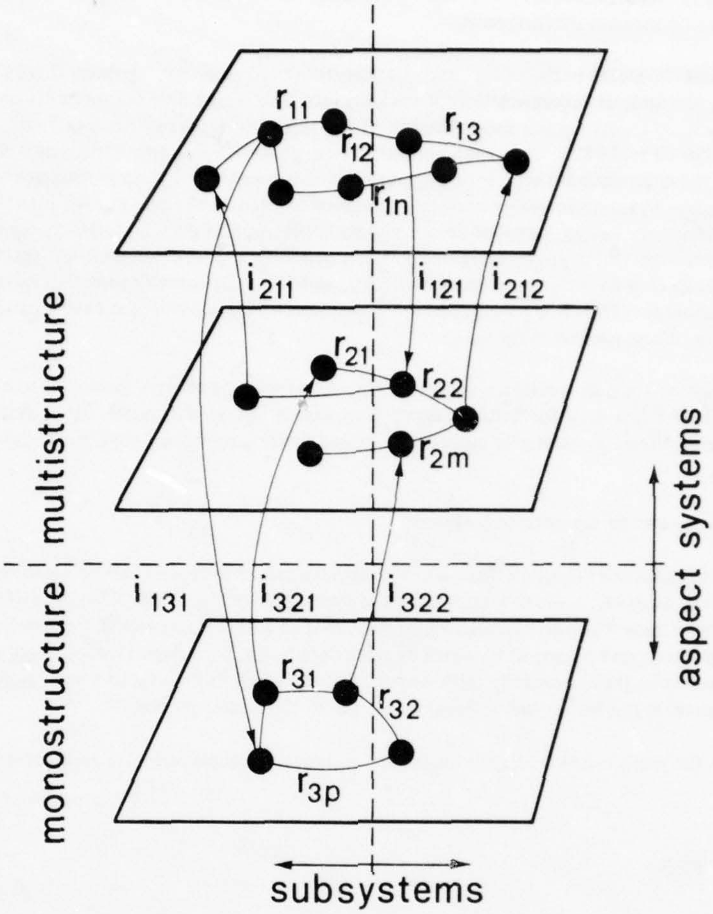

Fig.2.2 Monostructures and multistructure

they comprise a subsystem in the sense of the foregoing definition. They are also flow systems, because they are a function of time.

Flow systems characteristically include a casual relevancy between the input and output variables forming the dynamic characteristics of the system. The dependent variables must be controllable in some way and may be a combination of information (data and instructions), energy and matter. One way to analyze flow systems is by a flow diagram which shows where decisions can be taken whether or not to proceed depending upon the circumstances. Special symbols, as in Figure 2.3, have been proposed for such activity[9]. See Section 3 (Mission Analysis).

Process activities, whether they be manual, mechanical, electronic or otherwise, generally include branching points. If the choice of action or decision at these points is vague, i.e. not fully determined by previous operations in the process, the composite activity is a procedure. Such points may also depend on independent internal states in the system and external states in the environment of the system. The vagueness at the branching points requires some higher order decision strategy, often conveniently provided by a human operator. If the MMS is to be fully controllable, this decision strategy must also be considered in the design of the MMS. Sometimes it is possible to implement the strategy in some intelligent machine, capable of taking optimum decisions in fuzzy situations.

If, however, the choice of action is fully determined by the structure and the previous operations, the composite activity is a programme or algorithm instead of a procedure. Programmes or algorithms are also subsystems and quite commonly used, for example in computer software and in many industrial and military activities.

2.2.3 Other Structures

Procedures, programmes and algorithms are activity structures which can only be designed in detail once the decision is taken which equipment is going to be used for what purpose. To arrive at that decision in a methodical fashion, we will introduce at this point other kinds of system structures[6,10] to facilitate the breakdown of the MMS in levels of descending hierarchical order or in increasingly finer detail and in functional parts with well defined interfaces.

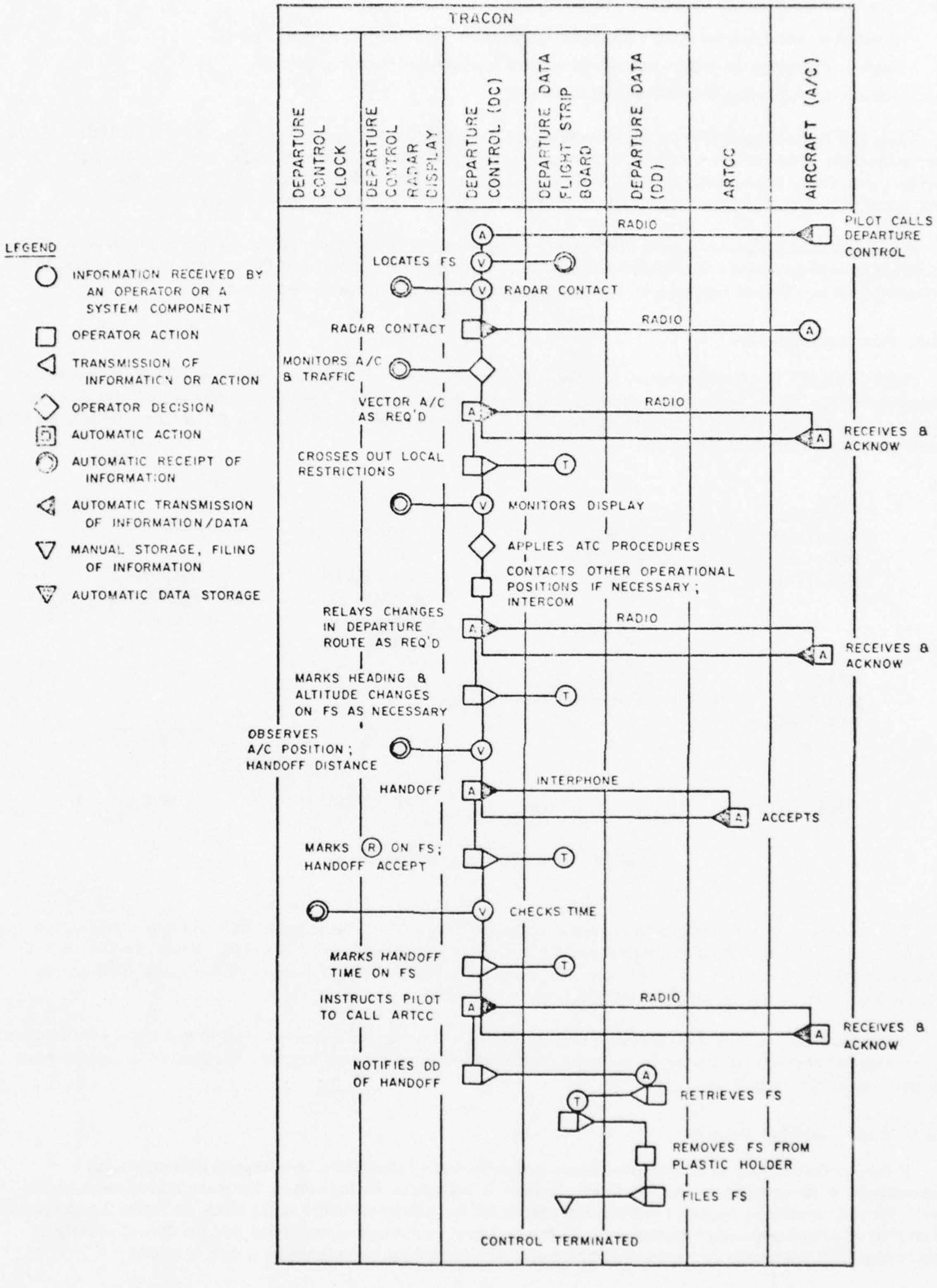

Fig.2.3 Operational sequence for IFR departure[10]

Analysis in terms of structures is desirable for every aspect where nodal points either are necessary or unavoidable. Many types of structure can be conceived; for example:

- functional, describing the system functions which follow from the list of requirements;
- organic, describing the system in terms of selected hardware/software/equipment;
- socio-technical, giving man-machine interrelations.

These goal-related aspect systems are very important for the methodical reduction and analysis of the MMS and thus deserve adequate attention during design. Consideration will be limited here mainly to these three types since these determine to a large extent the capabilities of the MMS and an understanding of their tasks by the personnel involved: the inner aspect (architectonic) whose ergonomic significance is not sufficiently understood at the moment.

In order to meet the objectives, the MMS must accomplish a number of subfunctions in the system. In this context function is defined as: "mode of action by which it fulfils its purpose"[11]. In this case the action is that input variables are transformed into desired output variables. The variables can be matter, energy and information.

2.2.4 Functional Structure

An example of a functional structure is the general measuring channel: signal acquisition-conditioning-comparison-processing-display. This is a simple line structure. Applied to the primary function "aircraft navigation", the fact that there are two methods available to calculate present position, namely dead reckoning and position fixing, leads to a partly parallel structure as shown in Figure 2.4.

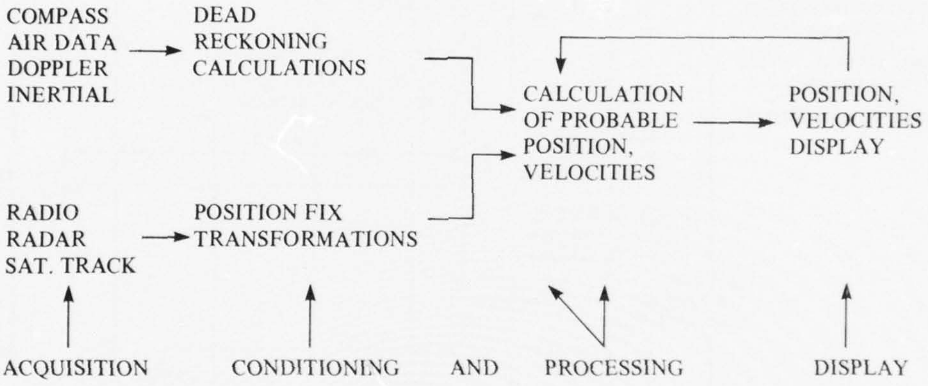

Fig.2.4 Multisensor aircraft navigation

The closed loop on the extreme right is not essential for the functional structure as such, but may result from an integrity aspect which leads to the application of the method of recursive filtering. Thus the primary function is partitioned into a number of secondary or subfunctions, their choice already being influenced by aspects (conditions and constraints) which are derived from the set of system requirements.

It will be understood that the functional structure is much closer to the system purpose than is the organic structure. Technology and engineering provide the methods and means to implement each function; the organic structure models the anatomy of that realization.

2.2.5 Functional Flow Diagram

It follows that activity structures, procedures, programmes, and algorithms, co-operating with organs, are hierarchically at the same level. The functional structure, being generic for the organic structure, is at the next higher level. The functional flow diagram (FFD) is then generic for the activity structure of the MMS. In Figure 2.5 an example of an FFD of a radio position navigation subsystem is depicted; in this case exemplifying that the derived activity structure is fixed and mostly laid down in the hardware with limited human intervention, such as tuning.

The FFD shows the sequential relationship of the required tertiary functions which, combined in an algorithm specifically designed for that purpose, together constitute the secondary function "form position signals". This in turn is one of the constituents necessary to realize the main function of the subsystem namely to "compute and display present position in geodetic coordinates".

The same main function can be realized by the method employing inertial data instead of radio signals. Figure 2.6 shows the FFD of an inertial system.

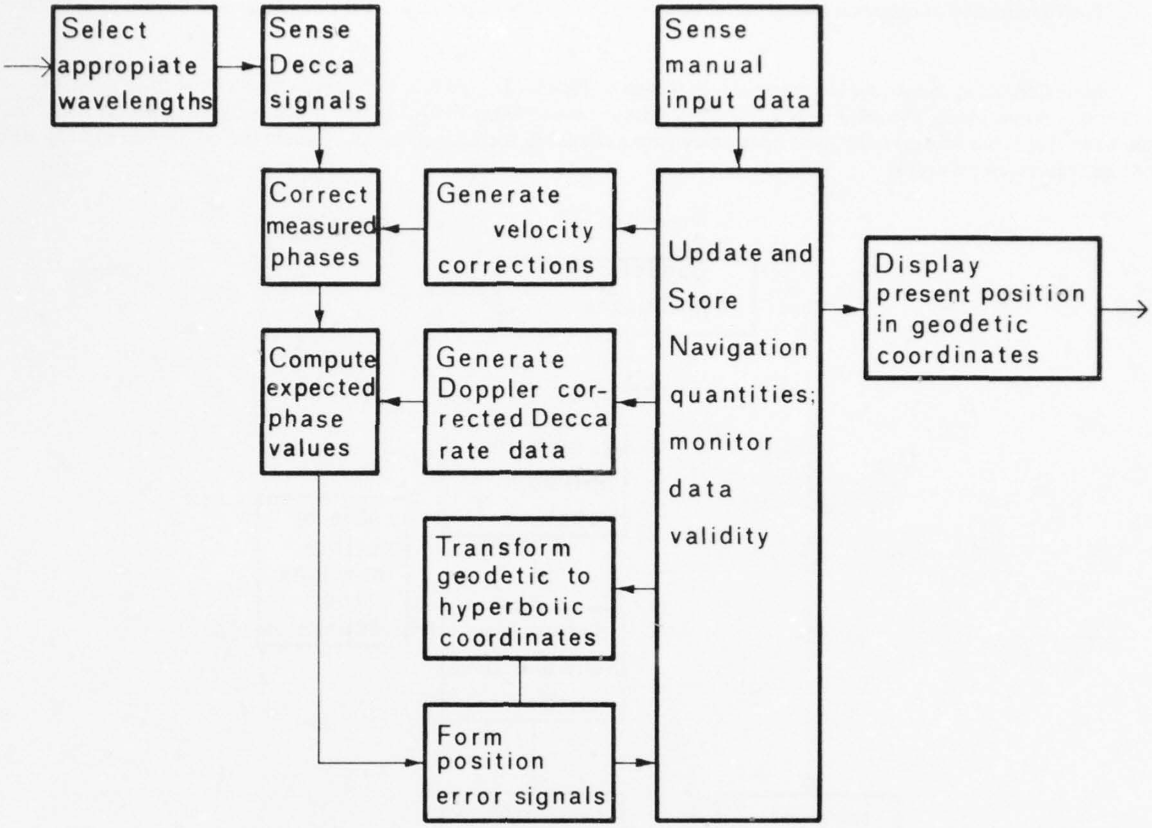

Fig.2.5 Functional flow diagram

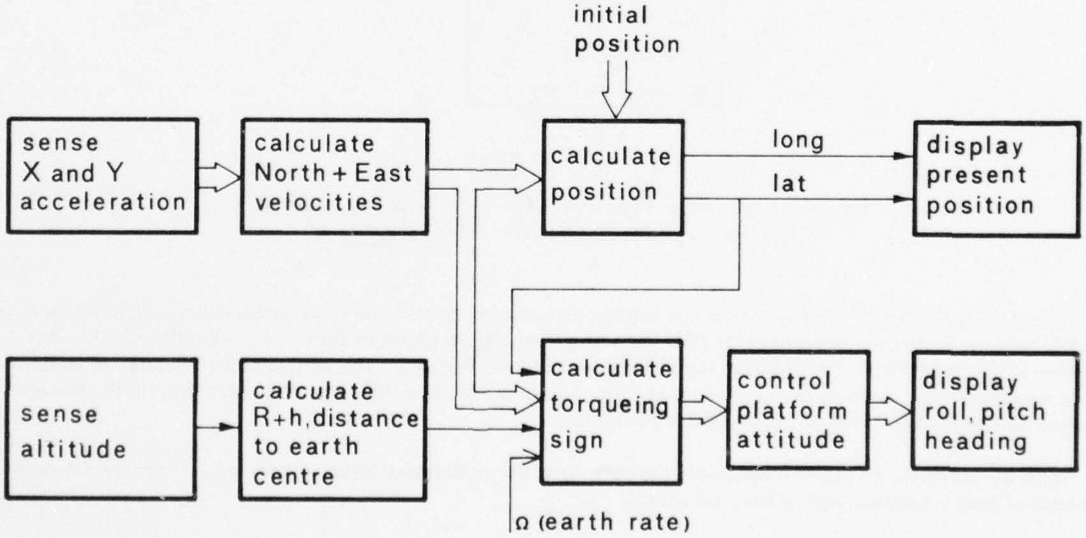

Fig.2.6 Functional flow diagram of inertial navigation subsystem

The functional flow diagram is also useful because of its ability to generate FFD's of higher and lower hierarchical order.

For example, in the sequential relationships shown in Figures 2.5 and 2.6, the closed arrows are seen to be of the internal relations class. The solid lines in Figure 2.7 show a lower order FFD with one block between closed arrows. On the other hand, the relations shown in open arrows are external to the subsystems, they show the interrelations in an FFD of higher hierarchical order.

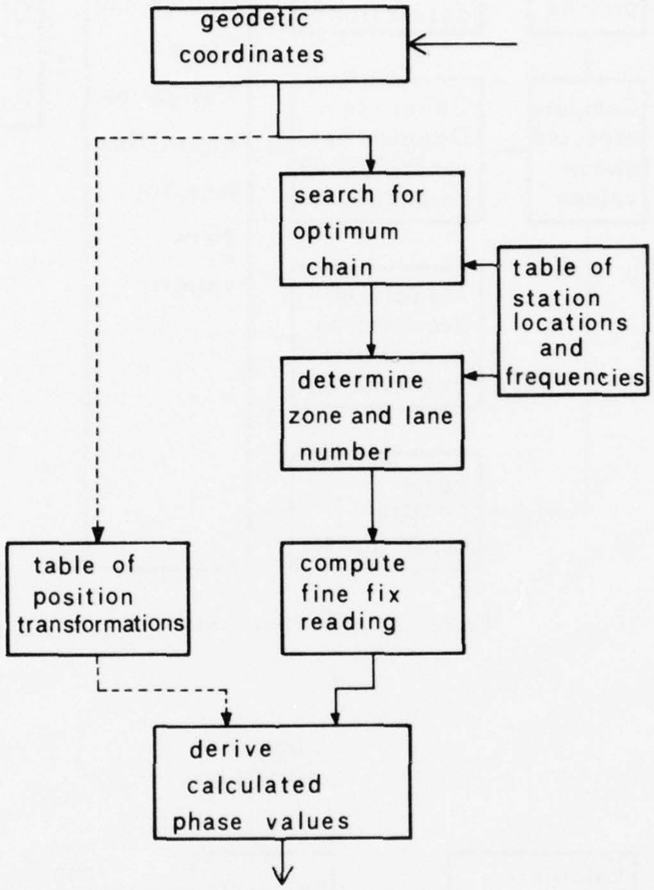

Fig.2.7 Lower order FFD for the block "Transform geodetic to hyperbolic coordinates" of the FFD of Figure 2.6

The tertiary functions defined in each box depend on a process carried out by procedural and material means. It is possible that the analysis of one particular FFD leads to alternative structures or even to new functions in the next higher or lower order FFD. For instance, the FFD of solid lines of Figure 2.7 can be traded for a large look-up table, shown by dotted lines, which lists phase values as a function of geodetic coordinates. This has effect on the storage function and on the operation of the navigation computer.

With the aid of the FFD the designer may, as early as in the exploratory phase, obtain insight into the required activities of both procedural and of material nature.

2.2.6 Organic Structure

The organic structure shows the distribution of equipment according to constructional criteria such as minimum wiring between boxes, equipment architecture, accessibility, maintenance aspects. A general purpose computer has a fixed organic structure, its function being controlled by the software. Changing the function means loading a different programme.

From this example it will be clear that the blocks in the organic structure are system components or subsystems. These blocks, by analogy, can be termed organs; a notion equivalent to that in biosciences where a hand or a liver are organs in a physically integrated subsystem, while the motoric nerve system is physically distributed subsystem. Organs are physically integrated sets of components or subsystems, designed for a small number of well defined functions in the total process of the system. In this sense, software modules or subroutines also comply with the definition. These organs are operated through programmes, algorithms or even procedures such that the specified functions are accomplished.

Figure 2.8 depicts the organic structure of a navigation system consisting of three sensor boxes, a navigation computer and a dedicated instrument panel. The four "boxes" are located in the radiorack or the instrument panel in the cockpit; this particular distribution being obvious when one considers the aspects of use and of maintenance.

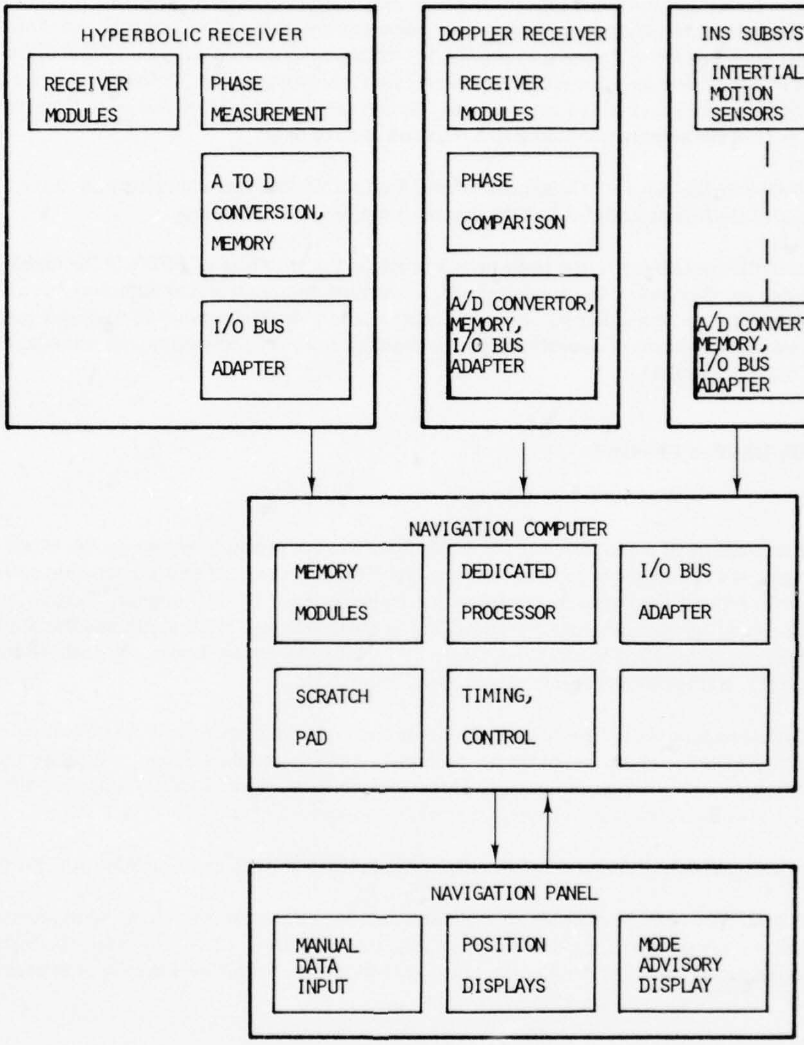

Fig.2.8 Organic structure

2.2.7 Socio-technical Structure

The socio-technical structure is the network of interrelations between human activities and equipment activities. It can be derived only when the activity allocation and the choice of the organic structure have been made. To this end the process-oriented procedures should be supplemented with equipment support activities, and with additional tasks as may be required by management.

After activity analysis it will become apparent that the activities can be grouped in four collections:

(a) Those performed by equipment only, in some cases monitored;

(b) Those carried out by human operators only;

(c) Those performed by either equipment or human operators, the choice being dependent on external conditions and/or constraints, possibly even being programmable;

(d) Which can only be done in cooperation between equipment and human operators.

The resulting activities can be grouped into tasks, which must be distributed in time such that the resulting jobs comply with biological and social needs and constraints. Activity allocation will be further discussed in 2.3.2.

2.2.8 Architecture

The organic structure determines considerably the perception of the system by the operator; in other words its sensory architecture. The pilot sees knobs and indicators which play a vital part in his navigation procedures, for example the maintenance crew sees boxes, connectors, cabling, energy-consumption, calibration controls, and status checks. To each operator a different aspect of the system is meaningful, for instance the instrument panel should bear a strong relation to the function of the system as perceived by the pilot. Different shapes, sizes, colours and other presentation aspects can help to identify partial functions of controls and displays (see Chapter 1), to facilitate their connection to procedures and to that part of his activity pertaining to navigation for example.

Figure 2.9 is illustrative in this respect. Composite activities allocated to human operators are tasks, their structure being derived from the contributing procedures and the system functions to be achieved.

The structure of activities pertaining to the tasks reveals much of the structure of FFD's in the (sub)system which together, in relation to one another and to the outside world, constitute the functional architecture. It manifests itself for instance by the length of procedural activities between decision points, by the number of decisions per unit of time, by possible combinations and sequences of operations, by the required selection, education and training, by work-rest cycles and so on (see Chapters 3 and 4).

2.3 DIVISION OF THE DESIGN EFFORT

2.3.1 Introduction

It is essential that at the start of a design effort the MMS objectives are precisely known to the future user; to the extent that these are vague, the resulting system will be imprecise. It is also essential that the user has sufficient wisdom to refrain from defining for himself the hardware configuration to be designed by the designer. Further, it is considered essential that both the user and the designer together translate the objectives into MMS requirements, and that they will agree on initial conditions and constraints of a general nature that shall apply to the design; e.g. cost ceiling, environmental factors, human factors, ethic and aesthetic considerations, (see Figure 2.9).

A number of analytical techniques are applicable. The time span of development and design is divided into several phases (such as exploratory phase, analysis and planning, preliminary design, detailed design, test phase and operational introduction.[2,3,5] Partitioning of the design project into aspects which each require special mono-disciplinary attention (such as those concerned with the formation of project teams) also is common practice[12] (Fig.2.10).

Aspect systems provide the conditions and constraints in the process of implementing MMS functions!

Further, the MMS itself may operate in different regimes which lend themselves naturally to segmentation. For example, in aircraft these are the phases of flight (shelter, taxiing, take-off, cruise etc.). However, the following sections deal with the possibility of partitioning the design effort into general elements which always occur in each equipment design.

2.3.2 Structuring the Design Process

In each MMS both the man and the machine are process operators. Together they bring about a change of state in the environment of the system in accordance with the system objectives. Thus, the sum of the activities of the MMS is the function of the system as defined earlier.

In an aircraft, the sum of the activities of subsystems such as wings, fuselage, control system, propulsion, pilot etc. is to make the aircraft fly; which undeniably is the function of the MMS. Its objective could be to deliver, at a specified time and place, a load of objects in the form of matter. The same function of "controlled flight" can fulfill other objectives such as reconnaissance (a load in the form of information), recreation (pleasure flying, airborne broadcast of TV programmes), or system validation (flight testing of airborne equipment).

This simple example illustrates how different objectives can be achieved by the same function, (see upper part of Figure 2.11). Every function is carried out by a suitable combination of human and material activities; i.e. each function is realized by a chosen *method*. Generally, there is not a one to one relationship between function and method, because for the realization of a function often several methods can be used (see Figure 2.11).

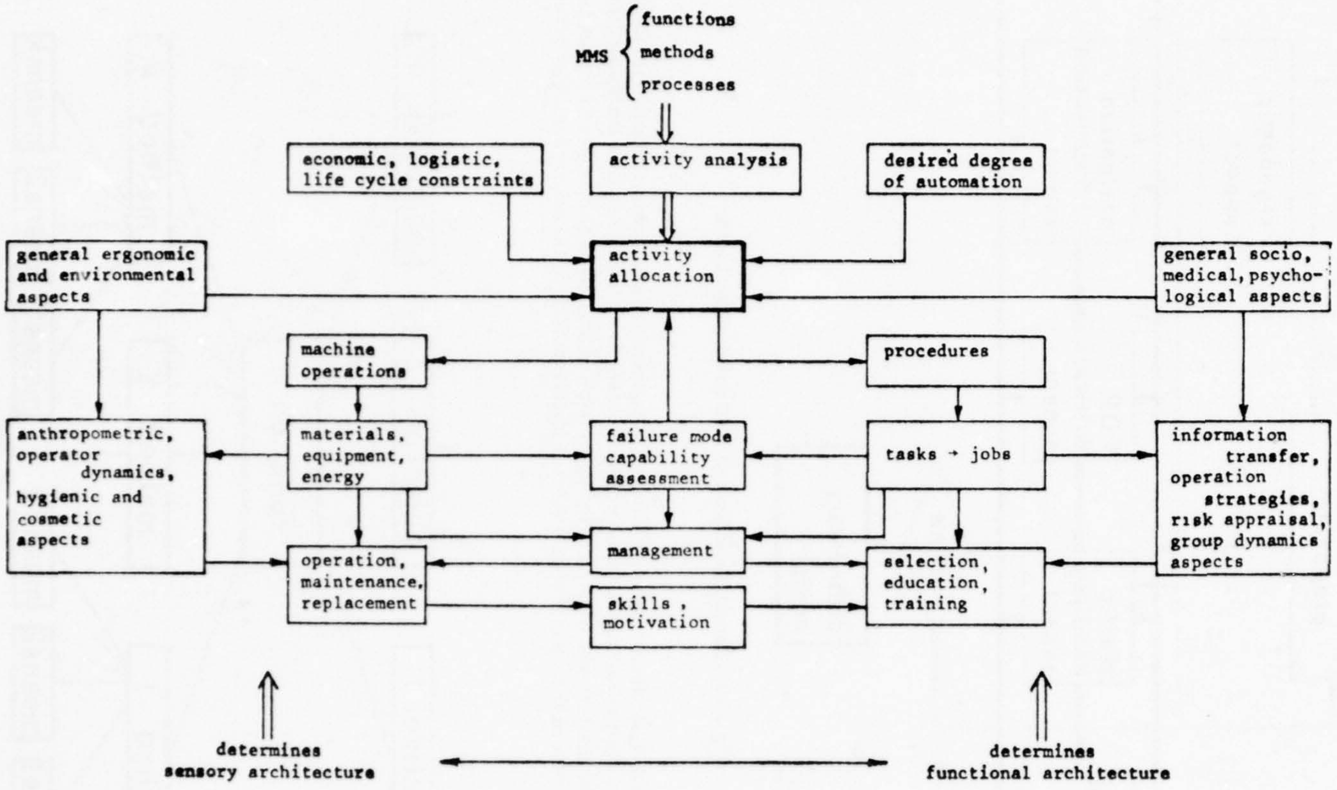

Fig.2.9 General synthesis diagram with activity allocation in the central position

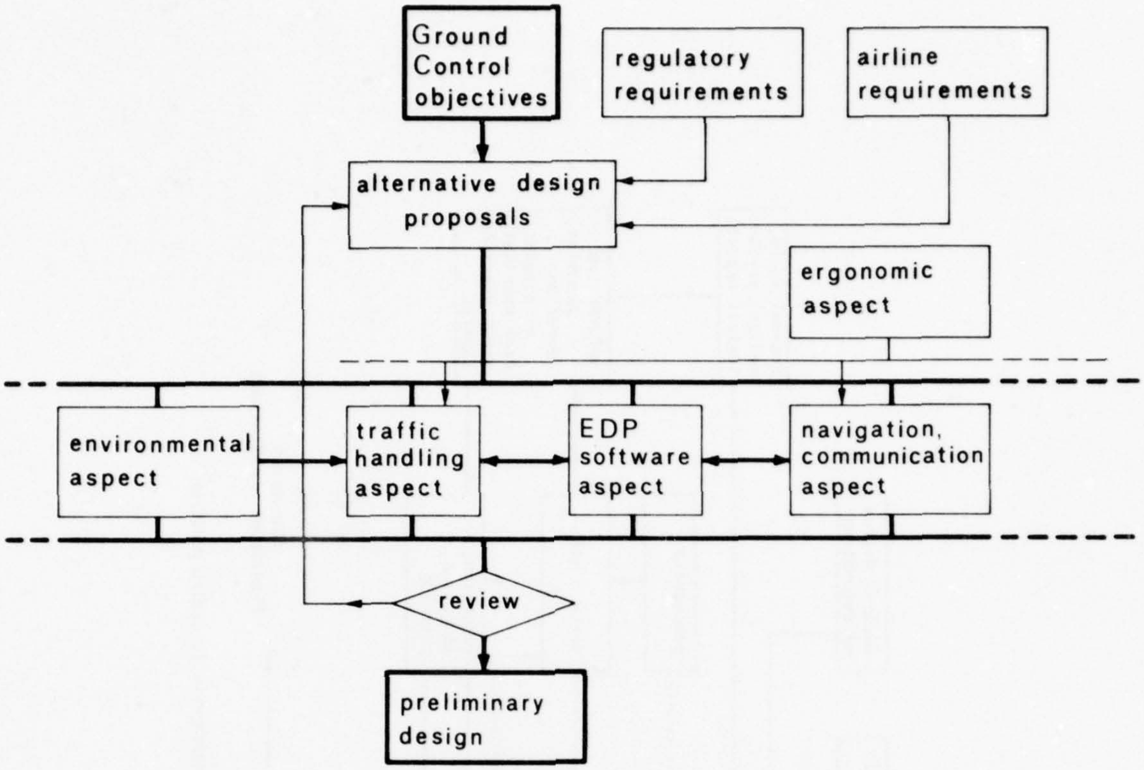

Fig.2.10 Aspect breakdown of ATC design project team

Once a particular method is selected, there are a variety of equipment and procedures (*means*) for its implementation. Thus the methodical analysis can lead to a tree with a very wide base. In order to keep the design effort within acceptable proportions one must be very selective in the upper levels of analysis (requirement and function, possibly also method); using preknowledge of the possible effects at lower levels especially in the area of human activities (e.g. degree of automation).

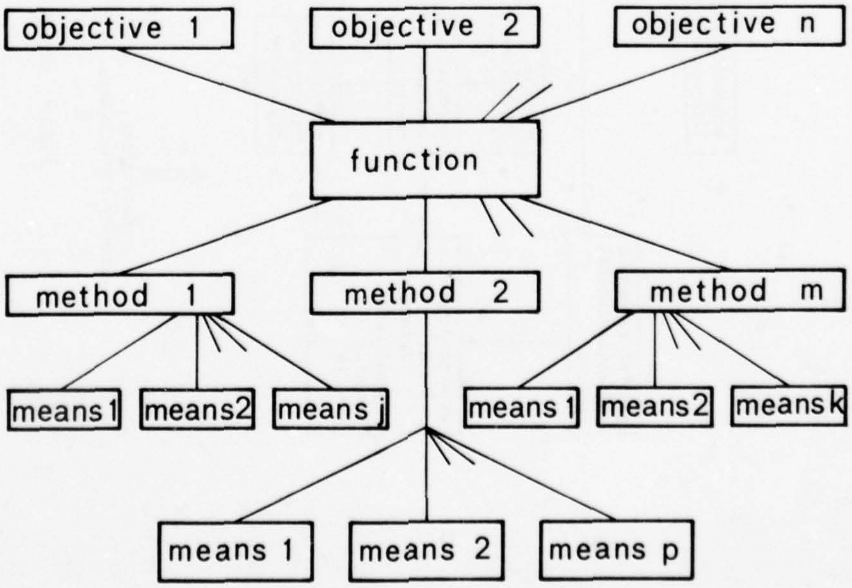

Fig.2.11 Realization tree with "function" in the central position

In Figure 2.11 a realization tree is depicted with the notion of "function" in the central position. This situation occurs for mass produced "general purpose" equipment. Usually the designer is unaware of the precise objectives of its user; most computers belong to this class.

Conversely, in the design of goal-directed or dedicated equipment, this realisation tree must have only the precisely known system objectives as its central sources; it becomes the MMS design tree. The tree characteristic is, for obvious reasons, often not shown in block diagrams of design processes. In terms of system structures (2.2.3), the relation with the subsequent level of Figure 2.11 is shown in Figure 2.12.

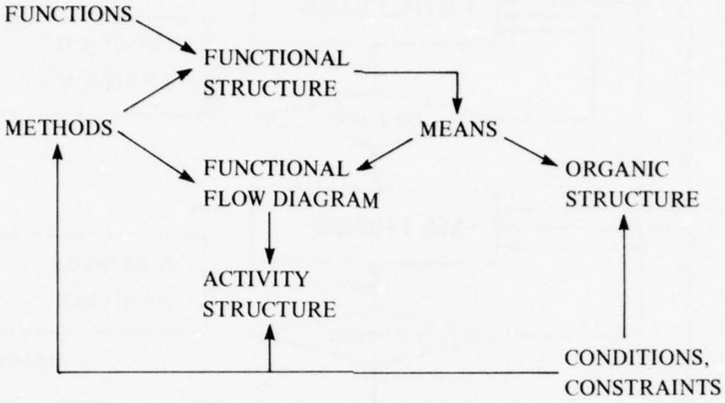

Fig.2.12 MMS design tree

A typical example of the design process, but extremely simplified in order to emphasize the basic "objectives-functions-methods-means" sequence, is shown in Figure 2.13.

Reiteration, so characteristic for every creative process, is symbolized by the many feedback loops. For instance, take the block "Transform geodetic to hyperbolic coordinations" in Figures 2.5 and 2.7. This function can be realized with

(a) the aid of a look-up table: or

(b) a coordinate transformation computation.

The choice has consequences on both computation time and storage volume. In the case that "computation" is chosen, the designer is still free to

(c) operate directly on the original analog signal format, or

(d) to choose for A/D conversion. This has consequences on weight, power consumption, accuracy.

He may also choose

(e) open loop, or

(f) a feed back type computation.

Thus he has in this example six alternative methods to realize the partial function.

Reiteration takes place by comparison with the alternatives of other partial functions, by comparing against initial design conditions and using practical reasoning. The latter would probably point to the combination (ade): digital open loop, full look-up table; because a digital signal format is already required for reasons of accuracy, and Programmable Read Only Memory (PROM) is easy to use and much cheaper than other digital alternatives. This shows that the implementation (PROM) influenced the choice of the method – (ade) instead of (bde) or (bdf) because of another (economic) aspect.

This example illustrates the review sequence. A similar method can be applied to more complex designs. A computer may be used to aid the design and assist in the selection of alternatives by predicting composite consequences at an operations or systems level.

The allocation of activities to men, the grouping of activities into procedures, then into tasks and into jobs, requires organizational discipline in the design project, as shown in Figure 2.9. An example of the relative freedom in allocation is found in the auto-pilot as a back-up device for the human pilot. This has inner loop and outer loop aspects. The inner loop may contain such items as the stabilization and control servo's and actuators. The outer loop employs flight data and provides course feedback.

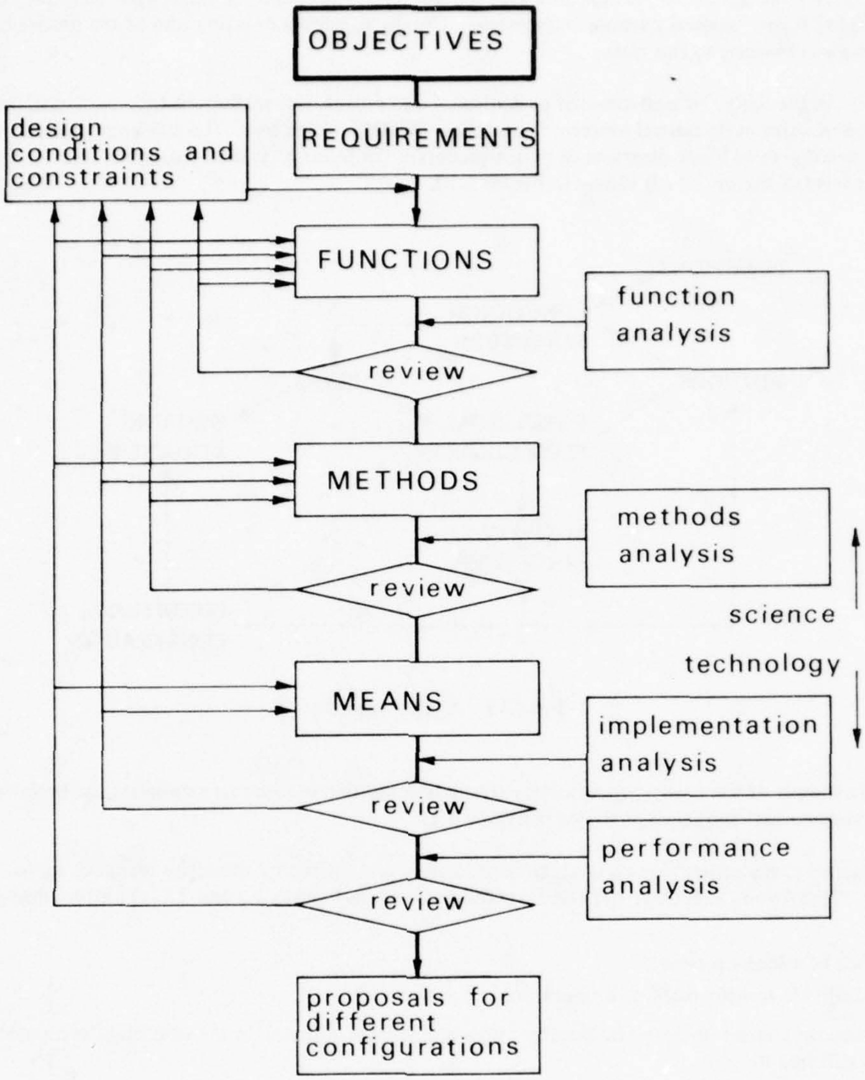

Fig.2.13 Reiterative design loops

The operation of the inner loop may depend on datum control signals from the human pilot, or actually be controlled by a human pilot, or be fully automatic. The same is true for the outer loop, and every combination is open to the designer. His choice shall, among others, depend on his knowledge of the capabilities of the average pilot. As such, Figure 2.9 illustrates much of the subject matter of this advisory report.

The performance of the MMS depends on the weighted sums of the capabilities of both the technological part of the system and the human operator, involving the degree of matching between system properties (equipment, process activities) and human factors such as inner representation or mental model; information handling capacity; motoric and mental skills, selection and training.

2.4 THE HUMAN FACTOR

In the activity analysis and the subsequent activity allocation of Figure 2.9 the relationships of aspects including timing, speed, accuracy, computation, energy expenditure, and strength become tangible. They can also be identified quantitatively. Those activities which lie within the human aspects profile, can be allocated to man.

Traditionally, the operators' ability to perform a specified task is measured following an outline of aspects such as listed in Table 2.1.

This table is suggested by V. David Hopkin[13], which gives an excellent exposé of human factors in the ground control of aircraft.

TABLE 2.1

1. Biographical requirements: age, sex, nationality, experience in job, other relevant experience.
2. Physical and Physiological requirements: attainment of medical standards, general health, physique, strength, endurance of or resistance to fatigue, tolerance of minor physical environmental stresses, adaptability to work/rest cycles.
3. Sensory requirements: auditory, visual, tactile, kinaesthetic, sensory interactions.
4. Perceptual requirements: speed, accuracy and ability to discriminate in each sense modality.
5. Information processing requirements.
6. Psychomotor requirements: muscular co-ordination, fine co-ordination, dexterity, manipulative abilities, compatibility between stimulus and response.
7. Verbal requirements: language(s) spoken and understood, verbal fluency, clarity of expression.
8. Knowledge and Skill requirements: academic knowledge, practical knowledge, training records, ability to apply knowledge, skill in job procedures, practical judgement.
9. Educational requirements: basic educational qualifications, additional qualifications recent attainments, courses attended, future education.
10. Mental and Cognitive requirements: general intelligence, verbal, numerical, spatial and mechanical abilities and aptitudes, reasoning, short term and long term memory, ability to innovate, flexibility of thinking, ability to learn from experience, ability to forget or discard inappropriate behaviour.
11. Clerical requirements: speed and accuracy in associated sensory, perceptual, intellectual and psychomotor functions, preparation and use of job aids.
12. Personal requirements: general personality, specific personality traits, personality profile, personal appearance and habits.
13. Social requirements: ability as a team member, tact, leadership, morale, attitudes towards superiors, attitudes towards subordinates.
14. Interests and Motivational requirements: activities and behaviour which reflect job interest and job satisfaction, need for challenge and effort in job, opportunities to use skills.
15. Emotional requirements: emotional stability, perseverance, tolerance of varying workload conditions, response to stress, response to boredom.

Since these aspects are, within the boundaries of their variability, fixed data it is necessary to compare the required level of effort against the human endurance profile.

Many human factors handbooks[20] provide such data. Endurance is highly variable but also adaptive: mathematical models such as transfer functions must account for such non-linearity in actual stress conditions. Man could be conceived of as a cybernetic being; with the ability to make decisions under ambiguous circumstances, able to learn and to change his mind, to test and to validate, to falsify, or to judge usefulness; each change of state adding to his experience. Psychic stimulus/response (SR) models can be tested particularly in a simulated environment with various conditions of (goal-derived) mental and physical load. The operator's activity can be far more complicated than the designer's activity analysis predicted, and every action is an opportunity for error. Human reliability thus has become the object of study[14,15].

As a pilot, man will use his own sensors and his observation of indicators to control both the inner and outer loop. His ability to coordinate and his social attributes are called upon when other poeople, in the aircraft or on the ground, are also involved in the task. A generalized diagram of factors contributing to man in a control task is depicted in Figure 2.14.

Three basic areas can be recognized: the general aspects of workplace, job and education; and the loops (1) and (2).

The second loop has received the most attention for the last thirty years[17,18] and is known as the control loop or "inner loop". Governing parameters are vehicle dynamics and physiological speed limitations (neuro-muscular dynamics and so on).

The first loop (decision loop or "outer loop") is of a much more complicated nature, involving cognitive abilities and limitations of the human factor[19] which are mission dependent. Few research results in this area are available to designers and the limited data available, falls short of the requirements concerning optimization of MMS capability through better use of human resources. It is highly advisable to direct more research to the cognitive elements contributing to the success of the mission, but in an engineering, quantitative fashion.

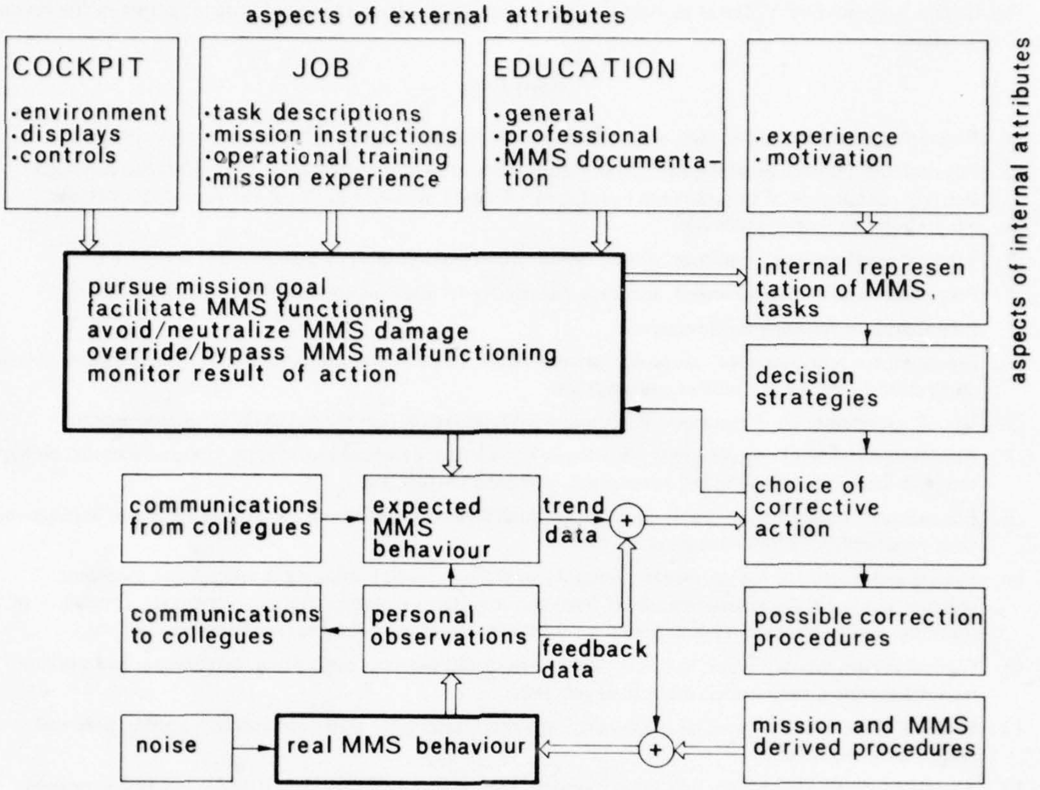

Fig.2.14 Aspects of internal attributes

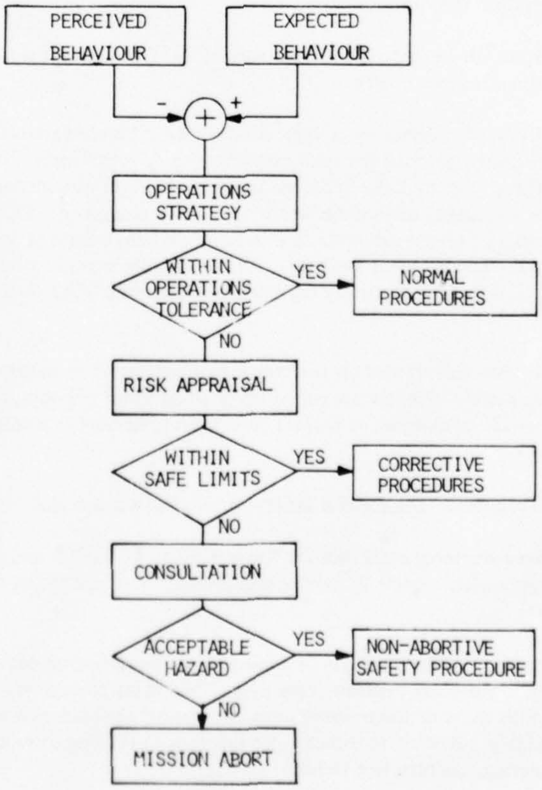

Fig.2.15 Selection in internal programmes in decision loop

The third area is that of the educated, trained, still learning human processor using his short term and long term memories, and psychomotor skills. These are applied under the influence of human reactions, needs and constraints, such as fright factor, motivation, overload, adaptability, habits. Education, and his individual view of his own role, largely determine the pilot's internal representation of his work[16]. Being highly personal, it can deviate considerably from the designer's image of the work, the cockpit and the pilot. Consequently, designers must keep in close touch with pilots so as not to stretch their adaptability too much and, vice versa, non-natural parts of the pilot's task must be trained to the extent that the internal representation of pilots become congruent as required in high-stress situations.

Good, transparent functional and socio-technical structures of the MMS are a great help to cope with unforeseen situations: one cannot depend solely on thorough training and briefing of the pilot. Moreover, in a well-designed MMS the learning period will be shorter.

Decisions strategies are closely connected to the operator's internal representation of the MMS. Generally, they are formed during instruction and excercises, and improved through mission experience. In turn they determine the choice of a specific (corrective) action, given feedback and trend data on the behaviour of the aircraft. As the flying experience increases, the pilot relies more on predictions of trended data for his choice of corrective action. Also during periods of mental stress there is a tendency to relieve the workload in this manner.

Corrective action is applied only when the actual situation is considered to be deviating from the desired. The latter is effected in an open loop fashion, exemplified by the Figure 2.14 box "mission and MMS derived procedures", which also would include basic conditions for functioning of the biological system.

Both open loop and corrective decision loop procedures consist of sequences of partial programmes, their type and sequence being adapted to what in the actual situation is needed, (see Figure 2.15). Such procedures must, of necessity, be part of the MMS design if several MMS are to behave in exactly the same way with comparable stimuli.

The partial programmes should be overlearned patterns, which are carried out almost subconsciously with the required degree of precision.

However, the choice of such partial programmes and their sequencing is not always a routine matter and can pose a decision load on the operator. The strains of unexpected events requiring quick evaluation and corrective action, can over burden the pilot. The normal procedures which are mission and MMS oriented should allow for sufficient reserve capacity in this respect.

2.5 CONCLUDING REMARKS

In the design of aircraft a most important factor is the balance obtained in matching the pilot's inner representation of the MMS, its objectives and his power to achieve them, to the MMS functional architecture as conceived by the designer. The functional architecture is largely determined in the definition phase and preliminary design phase of a project; and with it the degree of use of pilot's capabilities as a system controller. For that reason ergonomic considerations must guide the conception of new aircraft and its parts. The sensory architecture is mainly determined in the realization phase and anthropometric, physiological and information handling requirements must be met.

Currently, modern technology is providing means for obtaining valid behavioral data in simulators. Additionally, feedback from actual pilot's experience provides important qualitative information. Such procedures, however, are ill suited to computer assisted design methods. Thus it will be in the interest of the aerospace community to direct part of its research potential to the non-technical man-machine interface aspects with the aim of obtaining harder, useable data leading to more precise elements in the MMS capability matrix.

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Section 2

CHAPTER 3

PILOT WORKLOAD QUANTIFICATION FOR AVIONICS DESIGN

Recent avionics development has been in the direction of increasing complexity, cost, and separation of aircraft control from the human pilot. One current underlying philosophy in avionics design seems to be to remove aircraft control from the human pilot whenever the required flight profile requires him to handle flight information at a rate beyond his inherent capability. This philosophy has probably resulted in avionics over-automation. A properly posed avionics system design problem should include human capability constraints cast in systems engineering terms. It is this modelling of human capability which will be treated here.

3.1 CONTROL THEORETIC HUMAN OPERATOR MODEL

The basic tenet of human operator modelling is that a pilot is an information processor-controller comprising an element in a control loop. The goal of this approach is to describe the operator mathematically so that a total system engineering analysis can be performed on the aircraft using the pilot model. A complete model should feature control adaptivity and discreet decision processes; however, as a beginning, far more tractable models can be constructed (and experimentally verified) by considering the case of a human operator in a statistically stationary feedback control situation.

This viewpoint is clearly evident in two human operator models, which have received widespread attention, the crossover model of McRuer[1] and the optimal control model of Kleinman[2]. The former has provided a basic understanding of how the human operator adapts to differing control tasks and has been generally successful in modelling the operator controlling simple, prototype plants while the latter lends itself more readily to complex plants characterised by a vector of states. Both models suffer from the requirement of system linearity and an imposition of considerable ad hoc structure. Additionally, workload modelling, which is certainly a central issue in avionics design, does not seem to be handled naturally by either model. Workload encompasses not only piloting tasks but also the stresses encountered in flying modern high-performance aircraft (e.g. 'g' forces, vibration, heat, hypoxia).

A state-of-the-art application of the optimal control model (Kleinman model) to the design of avionics equipment is provided by Hess[3]. In this report a helicopter flight director is designed to display an optimum number of limited variables in a desired priority and display configuration, which pilots will accept. The paramount feature of Hess' work is his derivation of a relationship between a minimum criterion function J( ) and the Cooper-Harper pilot rating scale[4]. Hence,

$$R_{CH} = R(J)$$

where R_{CH} is the Cooper-Harper rating and $R(J)$ is a monotone function of J; therefore, display configuration can be selected by a simulation which searches for the configuration which globally minimises J. While the utility of Hess' approach is not well established, it is an organised application of human operator modelling to avionics design. A natural extension of this approach would be to include economic factors in the criterion function and incorporate a more inclusive treatment of workload.

3.2 INFORMATION THEORETIC HUMAN OPERATOR MODEL

Man's inherent versatile adaptability is the single cogent argument for keeping him in the cockpit, but it also makes workload quantification difficult. Confronted with an increasing workload, the human controller will frequently maintain his performance in terms of traditional measures (mean square error, time on target) at a relatively constant level until a critical workload level is reached at which catastrophic failure occurs. This is depicted in Figure 3.1. Thus, predicting approach to the critical workload level W_c is a requirement of any model used in avionics design. Apparently acceptable performance may be demonstrated at workload levels near W_c but the overall system should not be rated satisfactory if a small increase in workload due to an additional stress (hypoxia, g-force) would result in catastrophic failure of the pilot-aircraft system.

A recent attempt to deal with pilot workload more directly marks a departure from traditional control-theoretic modelling of the human operator, in that information theoretic techniques are used to delineate functional information partitioning in the stressed human controller. It has features which suggest it may be useful in modelling for optimum avionics design. As this model is not widely available in the literature[5], it will be briefly discussed and a simple example provided. The imposed model structure is shown in Figure 3.2. The elements of the human operator model may be non-linear, time-varying, and noisy; in any case, they need not be specified a priori, or sought in the model's application. There are only three points which must be kept in mind:

(1) "Goodness" of performance is expressed in terms of entropy reduction, ΔH, due to loop closure, i.e.,

$$\Delta H = H(X) - H(E) \qquad (1)$$

where $H(\cdot)$ is entropy defined in the usual information theoretic sense

$$H(\alpha) = -\int \ln P\alpha(\delta)\, P\alpha(\delta) d\delta \, ,$$

and $P\alpha(\cdot)$ is a probability density function.

(2) The time evolution at any measure point in the model is assumed discreet (i.e., the data are sampled).

(3) The controlled element or plant is information preserving. Performance measure in terms of entropy takes some getting used to on the part of the systems analyst, who needs to recognize that entropy and variance are monotonically related for a large class of stochastic processes. The requirements of data in sampled form and a deterministic plant should present no significant restrictions.

The central mathematical result of the information theoretic model states that ΔH is always a difference between two information flows traversing the human operator, viz.,

$$\Delta H + I(X{:}Y) - I(E{:}Y) \qquad (2)$$

where

$$I(\alpha;\beta) = P\alpha,\beta(\delta,\eta) \ln \frac{P\alpha,\delta(\delta,\eta)}{P\alpha(\delta) P\beta(\eta)} d\delta d\eta$$

is the transinformation or information flow rate from α to β. Thus Equation (2) reveals that a given performance level may be achieved by a range of information flow partitions between the perturbing function X and the operator output Y, and the system error E and the operator output. Hence, even though performance in terms of ΔH (or equivalently, in most cases, mean square error) may remain unchanged for changing workloads, as shown in Figure 3.1, considerable adaptation may be taking place as the human operator divides his information processing capacity between the (X;Y) and (X;E) channels. That is, $I(X;Y)$ and $I(E;Y)$ may both increase or decrease together while ΔH remains constant. Bounds on maximum values of $I(X{:}Y)$ and $I(E{:}Y)$ will exist because of inherent human limitations on rates at which information can be perceived and processed by the CNS and actions executed by the neuromotor system. Such a bound is known as channel capacity in the language of information theory. These concepts are presented graphically in Figure 3.3 where isoentropic curves are shown for various levels of performance. The claim of the information theoretic model is that with increasing workload and constant performance, the operating point moves to the right along an isoentropic curve. This will be demonstrated in the example.

It is interesting to plot performance, ΔH, vs information flow in the (E:Y) channel as shown in Figure 3.4. Note that performance decreases rapidly (catastrophic failure) when the operator must process information at a rate exceeding the difference between his channel capacity and his established performance measured in entropy units; this difference is the maximum error processing rate for maintaining the specified level of performance.

Of course, the operator could "regress" to an isoentropic curve representing a lower level of performance which he could then maintain until increased workload again brought him to his error processing capacity for the new (and lower) level of performance. This "Entropic regression" is the information theoretic equivalent of McRuer's "crossover regression"[1]. Hence, the operator will either regress smoothly down a performance curve or will regress stepwise as shown by the dotted line in Figure 3.4. The precise manner of regression will depend on the task and rate of workload increase.

An example will now be presented which addressed the effect of requiring the operator to track increasing numbers of degress of freedom. Each degree of freedom is assumed to be tracked independently by a simple "gain" human operator controlling a "gain" plant. As shown in Figure 3.5. $\sigma_{n_i}{}^2$ is the noise variance of the instrument presenting the error associated with the i^th degree of freedom. In this example, it is assumed that the inherent instrument noise of each display device has variance $\sigma_d{}^2$ and that the attention fraction given to the i^th device is f_i. No other tasks are required of the operation; therefore

$$\sum_{i=1}^{n} f_i = 1$$

where $n \equiv$ number of degrees of freedom tracked, and according to a reasonably well verified model developed by Levison[6].

$$\sigma_{n_i}^2 = \frac{\sigma_d^2}{f_i} .$$

For the simple example presented here, we assume equal attention given to each instrument so that

$$f_i = \frac{1}{n}$$

and

$$\sigma_{n_i}^2 = \sigma_d^2 - n .$$

The perturbing function X is assumed to be stationary Gaussian random process with variance σ_x^2 and the noise associated with the display devices is also taken as Gaussian. Under these assumptions it is readily established that the loop gain-product for each degree of freedom, $K_{p_i}K_{c_i}$, must satisfy the quadratic equation

$$(K_{p_i}K_{c_i})^2 \left[\frac{\sigma_x^2}{\sigma_{n_i}^2} - e^{2\Delta H} \right] + 2\,\frac{\sigma_x^2}{\sigma_{n_i}^2} K_{p_i}K_{c_i} + \frac{\sigma_x^2}{\sigma_{n_i}^2}(1 - e^{2\Delta H}) = 0$$

which yields real solutions for $K_{p_i}K_{c_i}$ if and only if

$$\Delta H \leq \tfrac{1}{2} \ln\left(\frac{\sigma_x^2}{\sigma_{n_i}^2} + 1 \right) \quad ;$$

thus, the maximum performance bound for our example is

$$\Delta H_{max}/\text{deg of freedom} \approx \tfrac{1}{2} \ln\left(\frac{\sigma_x^2}{\sigma_d^2} \cdot \frac{1}{n} + 1 \right)$$

which is plotted in Figure 3.6 for several signal-to-noise ratios $\frac{\sigma_x^2}{\sigma_d^2}$. Note that if the *required* performance is in excess of this bound, control of some of the degrees of freedom must be handed off to avionics or a lower level of performance accepted. Also, the importance of display device design to minimize observation noise is clearly demonstrated. To demonstrate the use of the isoentropic curves, operating points for several workload levels are shown in Figure 3.7. Note that as workload increases $\left(\frac{\sigma_x^2}{\sigma_{n_i}^2} \text{ decreases} \right)$ the operating point moves to the right requiring concomitant increases in $I(X;Y)$ and $I(E;Y)$. Thus two important factors in optimum avionics design are the required performance level ΔH (usually mission determined) and the required information processing reserve (a safety factor). With these factors specified those designs achieving ΔH would be searched to determine which avionics configuration would result in operating points furthest to the left along the corresponding (to ΔH) isoentropic curve. Such a design would allow a maximum processing sense before channel capacity is exceeded.

3.3 SUMMARY

The information theoretic human operator model provides a natural context for quantifying pilot workload, designing optimum cockpit displays, and configurating avionics under workload constraints. It also embodies the principle that the pilot should share control with avionics instead of handing off control entirely. Research is currently underway to relate pilot rating scales (e.g. Cooper-Harper scale) to entropic workload measure.

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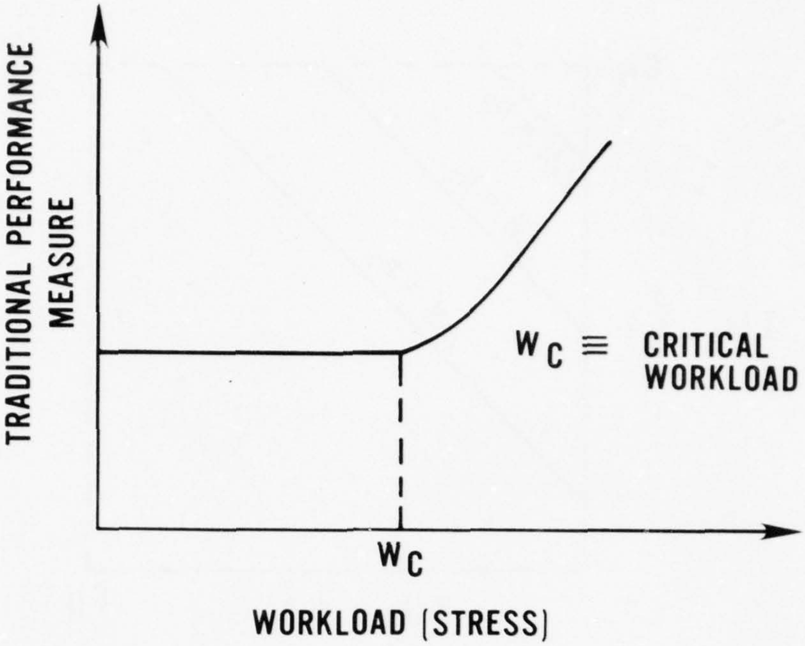


Fig.3.1 Critical workload

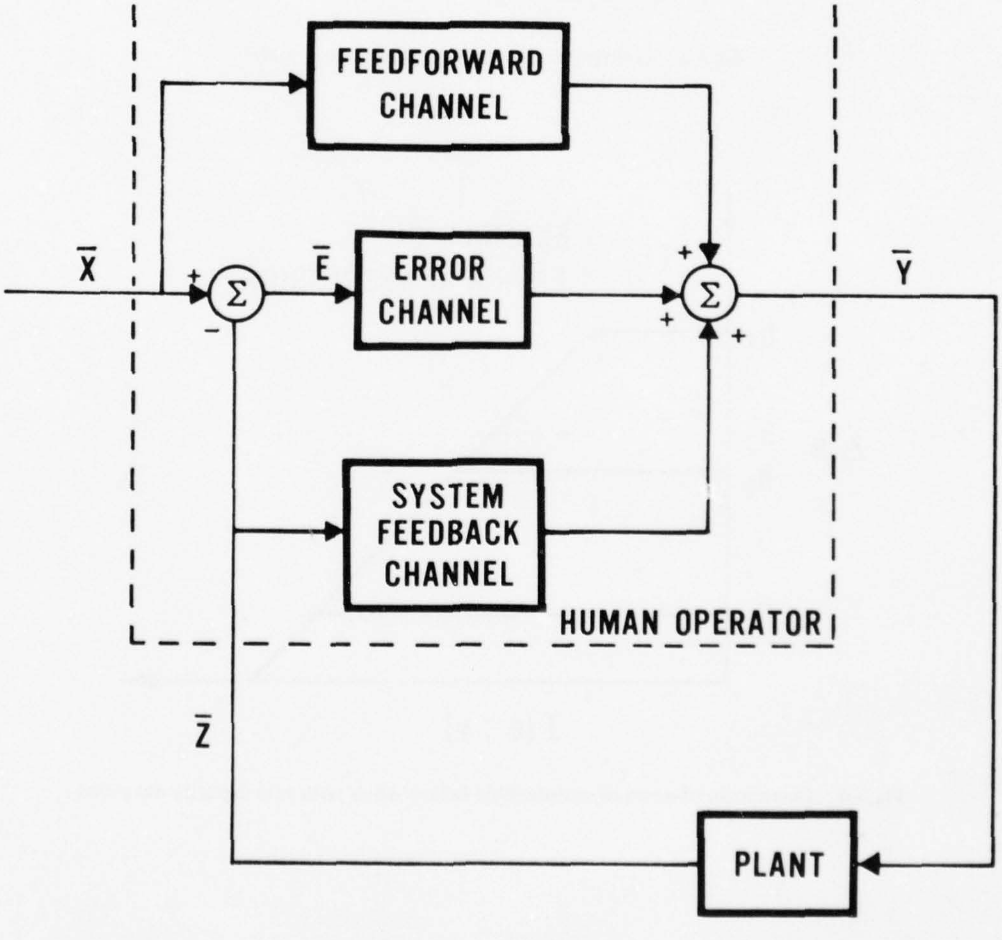


Fig.3.2 Human operator model

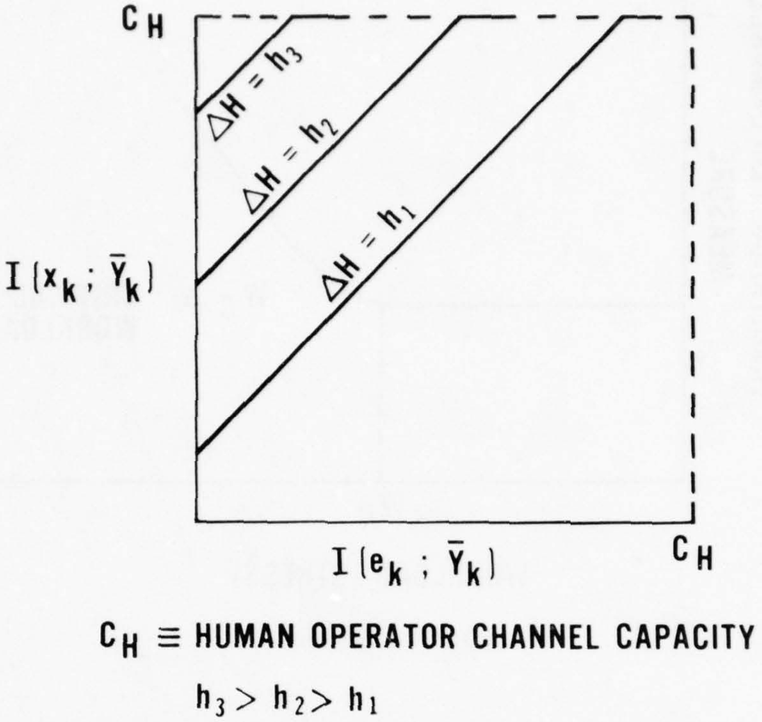


Fig.3.3 Isoentropic information partitioning curves

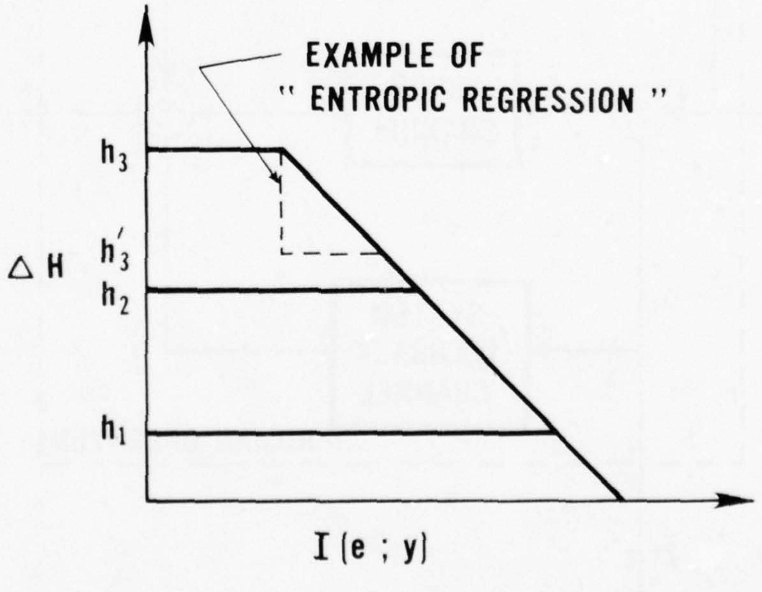


Fig.3.4 Illustration of onset of catastrophic failure when error rate capacity exceeded

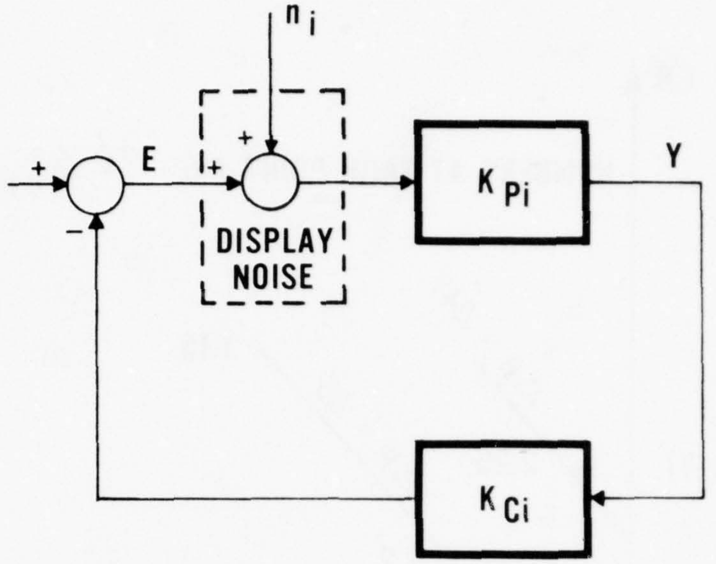


Fig.3.5 Mode for i^th^ degree of freedom

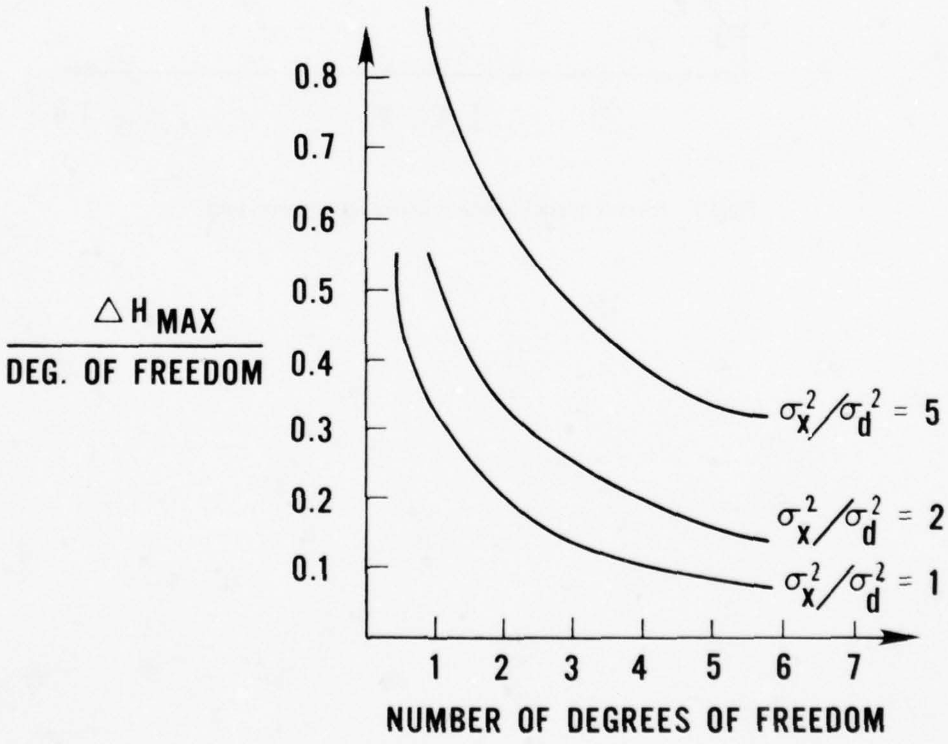


Fig.3.6 Performance bounds vs number of degrees of freedom tracked

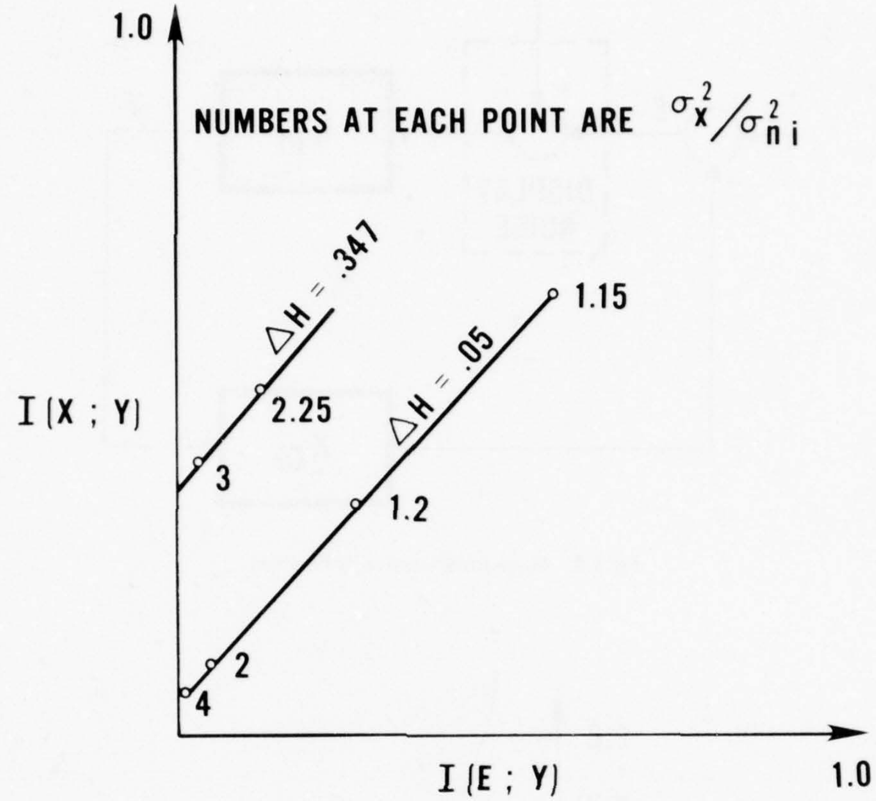


Fig.3.7 System operating points under varying workload

Section 2

CHAPTER 4

TRAINING IMPLICATIONS

4.1 INTRODUCTION

From the first fighter aircraft of World War I to the advanced systems of today, the fascination with technology has resulted in a tendency to optimize the equipment portion of a system, sometimes almost to exclusion of considerations for the human who must operate the system. This trend toward automation and sophisticated equipment has apparently contributed to the ever-increasing cost of aircraft. The purpose of this chapter is to review the concept of reducing the level of automation and increasing the responsibility for task completion to the man in the man-machine loop and possible implications for training.

4.1.1 Relationship Between Design and Training

As aircraft increase in complexity, both in terms of functional requirements and technological components, there is a high probability that longer and, consequently, more expensive training programs will have to be implemented for both operators and support personnel. Futhermore, designs do not always reflect that the pilot is not the only person involved. In operating and supporting a single aircraft, there must be a complement of highly skilled personnel. The relationship between the aircraft design and the content of the training program becomes a matter of concern because it is evident that training is expensive. The more complex the functional task, the greater the probability that more has to be expended for the required training, including training equipment.

4.1.2 Activity Allocation

It has been shown[9] that as aircraft requirements increase, avionics increase, maintenance increases, and costs increase. At some point in time – and that seems to be now – we must determine the maximum trade off in performance and cost. One approach is to reduce the complexity of the avionics, perhaps by placing more demands on the operator. In this chapter, we will look at man-machine interaction to see if the current reliance upon equipment to perform a function may be transferred to the operator without at the same time reducing unduly the performance of the system.

4.1.3 Scope of this Paper

This paper includes some elements which should be considered in the concept and design of future aircraft in relation to training requirements and costs – pilot capability, task analysis, individual/equipment interaction, support personnel, and planning a training program.

4.2 INDIVIDUAL AND EQUIPMENT TASKS

4.2.1 Individual/Equipment Interaction

If we modify (Fig.4.1) Bosman's general synthesis diagram (Chapter 2, Figure 2.9), it is evident that a thorough analysis becomes the key concept in planning a training program. The task analysis is a statement of the behavior required of the individual crew member to realize the mission requirements efficiently and effectively. The task may require interaction with equipment, but we will not consider equipment in detail other than in the context of increase or decrease in equipment dependence. Equipment dependence is the degree to which the successful completion of the task requires the use of the equipment; successful completion necessarily encompasses the idea of efficiency. If one views task completion as the sum of individual actions and equipment functions, it can be seen that for any single completion a set of interactions exists, all of which could result in the same outcome. The success of a task is dependent upon a ratio of equipment functions and individual functions (Fig.4.2). The task might be completed with equipment only (automation) or by the individual only (manual) or some combination of the two.

4.2.2 Degree of Automation

For example, we can consider the pilot's task of maintaining air speed sufficiently to maintain flight. This can be accomplished without instruments (by sound or feel) or with instruments (air speed indicator). In current aircraft, air

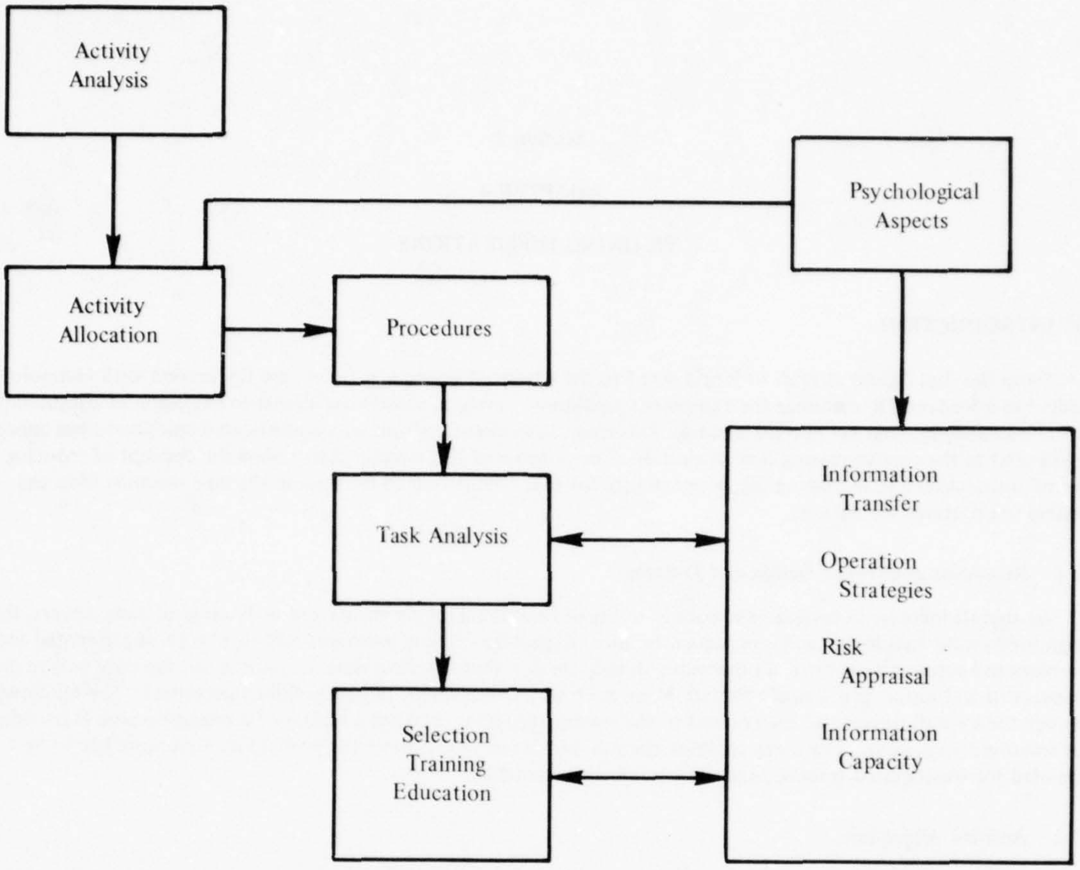


Fig.4.1 Modification of Bosman's general synthesis diagram

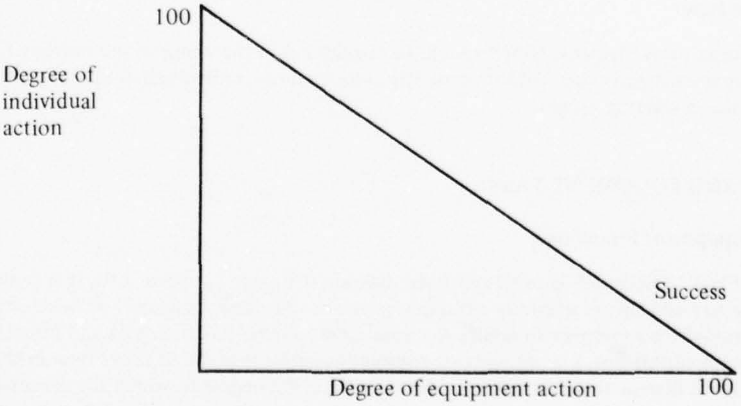


Fig.4.2 Ratio for task accomplishment

speed indicators are used which display airspeed in knots. The type of display can vary and the accuracy of display can vary. There might be an indicator which automatically checks airspeed against required speed and take appropriate corrective action without pilot intervention or monitoring and with greater precision. We have a situation in which varying combinations of equipment functions and individual capabilities can accomplish the task. The fully automated system would be a luxury, and its initial cost and ownership cost would probably be prohibitive. It may also provide more capability than is really necessary to meet mission requirements. It then becomes imperative to establish the requirements and constraints of system design before a decision may be made relative to the ratio of equipment versus individual to complete a task. In order to make this type of decision, a review of the strengths and weaknesses of equipment and individuals is necessary.

4.2.3 Individual/Equipment Comparison

In an effort to determine the ratio of individual/equipment (I-E) to complete a task, a general review of these components provides some guidance. As Bekey[1] points out, we need to consider some of the functional advantages and disadvantages of man and machine in a system to help in allocating the various functions in the man-machine system. Drawing upon available research, as very broad generalization can be made. Man is superior in making decisions in conditions of uncertainty, and equipment is superior for repetitious, well-defined functions. If we use the general idea of the functions of information processing, this generality is apparent. If a task is subdivided into data sensing, data processing, data transmission, and physical action, a rough approximation can be made of the relative degree of equipment versus the individual.

As indicated in Table 4.1, derived from Bekey[1] and Gagne[4], an individual appears to be superior in functions requiring modification during performance of a task although the constant advances in branching logic in machines may make this less clearcut. The individual can change action, generalize, and function in situations of uncertainty. Equipment is superior in sensing, processing, and providing data as long as there are clear specifications and signals. Equipment is also more reliable in repetitive activities (or functions) requiring excessive physical strength. It would seem appropriate to use equipment in a situation requiring clearly defined, repetitious functions. The individual should be used where change in activity may be necessary. In making decisions on the ratio of individual/equipment, other parameters must be considered.

TABLE 4.1

Comparison of Individual vs. Equipment

	Individual	*Equipment*
Data Sensing	Can monitor low probability events Sensitivity threshold low under favorable conditions Can detect masked signals in "noisy" conditions Can pick up peripheral data Resist jamming Amount processed low	Can monitor greater amounts of input, inputs out of human range Sensitivity threshold higher than man. Cannot handle unexpected events Poor signal detection in noise Probability data not picked up Subject to interference or jamming
Data Processing	Capability to generate strategies. Make decisions with minimal data Broad generalization capability Limited capacity to retain data Computational capability limited Overloads easily Short-term memory poor	High equipment reliability but cannot recognize and correct mistakes Extensive data capacity High computational capability Long-term storage data Short-term memory good Data retrieval capability Cannot generalize data inputs No creative function
Data Transmission	Can reformat or restructure with limited data Create or identify pattern trends Performance deteriorates with time due to fatigue, boredom, or distraction Relatively high response latency	Programmed presentations Limited flexibility in handling data Can handle large amounts of data over long periods with no deterioration Maintenance and quality control required Arbitrarily low response latencies possible
Physical Action	Can perform delicate functions Can handle multiple sets of actions Has adaptability Limited capacity of action Low strength range May require life support systems Emotional	Performs gross actions Has great strength No emotion Can perform repetitive actions Alternate actions not readily available Does not easily change once activity started

In making the ratio decision, the following factors should be considered: availability, physical size, energy consumption, support risk, and costs.

In evaluating these factors, we can again develop a table (Table 4.2) to clarify some of the strengths and weaknesses of each factor. From a review of these factors, it can be seen that an individual is a relatively low-cost, highly adaptable unit of small volume which generally requires non-goal-dedicated support. An equipment unit is highly variable and always requires some dedicated specialized support consideration; its loss is less critical, although there has been an increasing trend toward equipment which performs functions which man cannot replace if the equipment fails. Putting these two considerations together, it can be seen that for tasks which have high uncertainty, which require multiple actions which do not demand excessive strength and are not highly repetitive, an individual would be the better option. Reverse these conditions and we have an optimum situation for equipment.

TABLE 4.2

Limiting Parameters

	Individual	*Equipment*
Availability:	Large pool	Extensive amount
Physical Size:	Light in weight and bulk	Varies from small to excessively large
Energy Consumption:	Low	Low to high
Support:	Limited	Extreme
Reliability:	Moderate	Low
Danger:	Low-high	Low-high
Cost:	Low	Low-high
Loss:	Unacceptable	Acceptable

4.3 METHODS TO INCREASE AIRCREW CAPABILITY

4.3.1 Training Potential

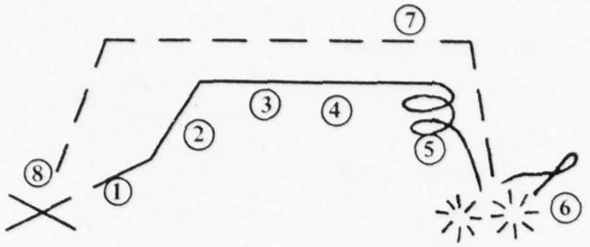
To examine the I-E interaction from a different aspect, we should consider why man began using tools or equipment. Initially man began using tools to increase or expand his physical capability. With our current level of technology, the trend has been to automate as much as possible to reduce the burden on the individual. If we wish to increase or expand the capability of the individual, we normally attempt to introduce some form of training to improve, increase, or expand the individual's capability. To improve the reliability of an established capability, the type of training we use is repetition. To increase capability, we introduce additional knowledge. To expand capability we teach a new strategy – a combination of repetition and new information. With a fixed task which has an established I-E ratio, we have two options to improve the task accomplishment either in terms of quality or quantity – new equipment or additional training. With the advances in technology, the tendency has been to increase dependence on equipment. When analysis indicates that additional equipment functions cost an excessive amount to acquire and maintain, the importance of considering alternative approaches to achieving the final design is rather forcefully brought to our attention. Such an approach is depicted in Bosman's Figure 2.13 and provides a procedure for balancing the relative cost of increasing the capability of the individual against the cost of equipment.

Unfortunately, the individual cannot be trained, *ad infinitum*, because of specific limitations, such as are described by Hartman. However, within the envelope of these limits, the individual's capabilities can be enhanced by training.

The specific functions which are more readily performed by the individual were covered in the discussion of Table 4.1. Within these constraints, we can assess the possibility of restructuring the pilot functions within a given aircraft for a specified mission to reduce the high cost of avionic equipment. In order to accomplish this, we have to look at a mission profile and some aircraft avionics configurations.

In selecting a mission to gain some insight into the functions required to accomplish the task, close air support (CAS) was selected. The example in Figure 4.3 indicates (in a gross way) a series of eight mission segments[2]. Each segment is sequential. It should be noted that different segments place different demands on the pilot. This also assumes that no emergency situations occur. Each of the eight segments consists of a different set of functions and each function demands a different interaction between the individual and equipment to complete the segment. Another mission profile, of course, could require another set of functions.

As can be seen in Table 4.3, a 1974 list of CAS avionics[12], the unit cost varied from $3,000 to $120,000. Some avionic equipment is used for multiple functions and other equipment is used for one special function. The final step would be to enumerate the subtasks to accomplish each mission segment and the ratio of individual/equipment to



PURPOSE
DESTROY DESIGNATED TARGETS
IN IMMEDIATE SUPPORT OF
GROUND FORCE OPERATIONS

MISSION SEGMENT	PRIMARY MISSION FUNCTIONS
1	SCRAMBLE TAKEOFF
2	CLIMB
3	CRUISE TO DESIGNATED AREA (FEBA)
4	LOITER ON STATION
	- COORDINATE WITH FORWARD AIR CONTROLLER (FAC)
5	DETECT AND IDENTIFY TARGETS
6	DELIVER WEAPONS (GUNS, BOMBS, AIR/GROUND MISSILES)
	- MULTIPLE PASSES, IF REQUIRED
7	RECOVER TO BASE
8	RELOAD, REFUEL, TAKEOFF ON NEXT SORTIE

Fig.4.3 Close air support of friendly ground forces

accomplish the task. Once this level of analysis has been achieved, a reapportionment of the ratio could be established to increase the individual functions and reduce the equipment functions. Any increase in individual functions would probably increase training requirements and, consequently, training costs. Should consideration be given to decreasing equipment costs by adding a second crew member to share the pilot tasks, those costs would have to be considered also. A question, then, is what the offsetting costs might be.

4.3.2 System Management Tasks

Although in the design of a weapon system, the pilot should not be considered as the only human element, for the purposes of the moment we must consider his limitations and capabilities as the executive in a human information processing system, a weapon system manager.

No longer can flying skills be considered a combination of a succession of perceptual-motor tasks and the efficiency of display reading. He must be able to deploy the aircraft under a diversity of conditions and perform multiple functions, such as interception, target identification and evaluation, missile launch, etc. He must be able to process a vast amount of information, often in a very short time frame. The pilot receives appropriate cues from the environment, processes and integrates these cues, and translates them into appropriate actions. This is very simply depicted in Figure 4.4 (Ref.5). To assist him in accomplishing his mission, he has been provided the most advanced equipment. He has been afforded the most advanced training to insure his proficiency. The support force has been trained, supplied, and managed to provide a combat-ready aircraft. This triad of man-machine-support insures the availability of a flexible instrument to carry out the varying missions.

4.3.3 Man as an Information Processing System

Some of the behavioral components, such as short-term memory, visual scanning techniques, target tracking, perception, verbal and motor skills, and divided attention, have been studied by many well-known investigators (Briggs, Broadbent, Conrad, Fitts, Fleishman, Poulton, et al.). Some parameters have been established . Because of man's adaptability and versatility, as well as the proverbial individual differences, it is difficult to set any precise limits to man's capacity to receive, process, and execute. Some forms of information received by humans can be quantified as bits, ranging, for example, from 2.8 bits per second for motor responses and 29 bits per second for verbal response to the same stimuli. In another study on channel capacity, indications were that real human information capacity approximates 40 to 50 bits per second, although the main bottleneck is probably in the brain[6].

TABLE 4.3

Conventional Close Air Support Avionics

Nomenclature	*Unit Cost*	*QPA*	*Annual Logistic Support Cost per Aircraft**
FM-622A VHF Communication Set	$ 7,503	1	$ 321
AN/ARC-51BX UHF Communication Set	5,706	1	613
AN/ARA-50 Direction Finder Group	4,726	1	79
AN/APX-72 IFF/Transponder Set	3,219	1	181
Horizontal Situation Indicator	3,040	1	530
AN/ARN-52 TACAN Set	6,735	1	628
AN/ARN-58A Instrument Landing System	15,852	1	97
AN/ARN-92 LORAN Set	99,730	1	438
AN/APN-141 Radar Altimeter	6,290	1	427
AN/APN-154 Beacon Radar	6,166	1	44
AN/APQ-126 Forward Looking Radar	119,351	1	2,877
AN/ASN-91 Tactical Computer Set	100,932	1	888
Air Data Computer System	13,242	1	827
AN/APN-190(V) Doppler Radar	39,189	1	1,193
AN/AVQ-7 Head-Up Display	50,148	1	2,165
AN/ASN-90(V) Inertial Measurement Unit	72,143	1	4,006
AN/ASN-99 Projected Map Display	22,011	1	293

Total avionics cost per aircraft = $575,983
Total annual logistic support cost per aircraft = $15,607
*IROS report, File number K051, PN3L, dated 1 Nov 74.

4.3.4 Establishing a Training Program

Most of the training programs are conducted on a basis of training the individual to reach a minimum level to be able to handle some activity. Every effort has been (and is continuing to be) made to identify those people capable of meeting training objectives. To extend that capability, however, we must train almost to a point of supersaturation. To train a pilot to fly an aircraft is one thing, to train him to fly well is another, and to train him to be a superior pilot and a system manager is still another. In Figure 4.5, a graphic display of this concept is provided.

Studies of skill acquisition[14] indicate that the process of minimum skill acquisition of a complex perceptual-motor skill is a three-level process: (1) Early (cognitive), (2) intermediate (fixation), and (3) late (autonomous). For a single skill, three levels of acquisition can be considered. After minimum skill has been accomplished, we must then address the special and supersaturated stages of training.

Obviously, before a training program can be established, the mission or missions assigned to the system must be clearly identified.

Instructional System Development (ISD), or the systems approach to training, has become the accepted approach in the US Air Force for determining course objectives and content. The ISD model may be considered to have five steps, with varying degrees of relevance to the present topic:

(1) Analyze system requirements,
(2) Define education or training requirements,
(3) Develop objectives and tests,
(4) Plan, develop, and validate instruction, and
(5) Conduct and evaluate instructions.

The first of these steps is certainly critical in determining operator performance requirements. A thorough task analysis – not just a listing of system requirements, but, rather, identification of the behavioural objectives of a task – is a critical and key element of a training program to enable the pilot to come closer to stretching the limits of his capacity.

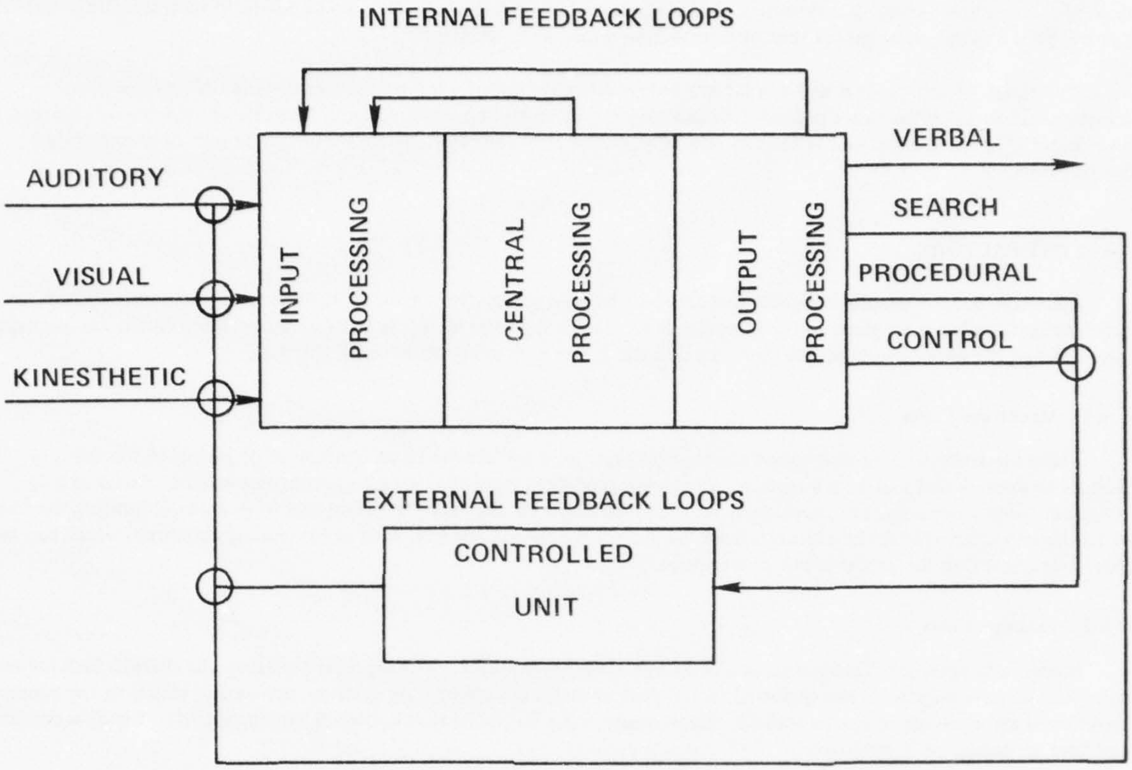


Fig.4.4 Model of the environmental composite system during flying training

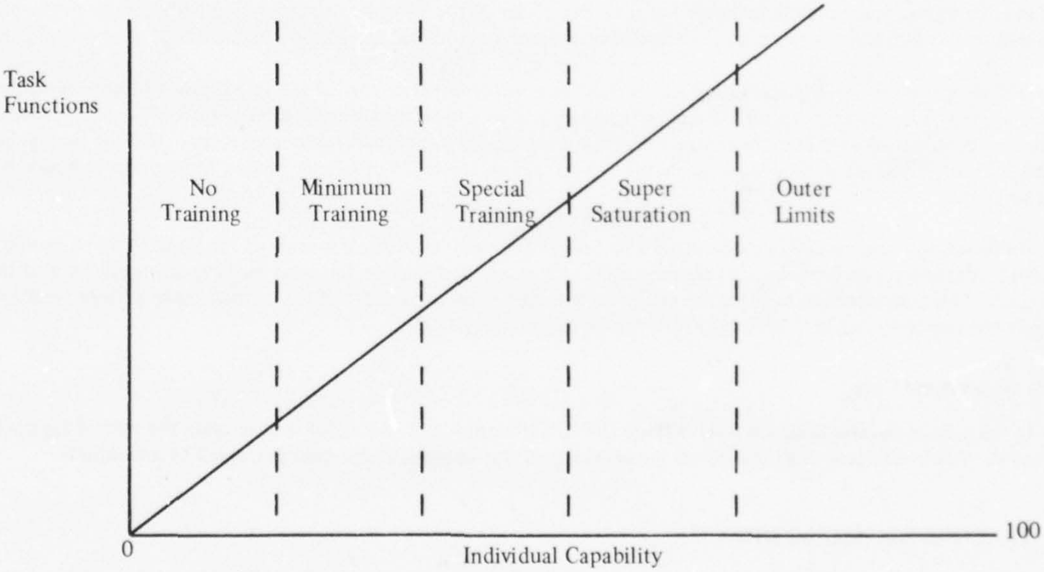


Fig.4.5 Levels of training to match task functions to capability

As indicated earlier, most of the research on various tasks of the pilot has examined perceptual/motor skills, tracking skills, scanning techniques, short-term memory, and limited divided attention studies. There has also been much effort on part-task and procedures trainers, crew trainers, some effort on massed versus distributed practice. Various investigators have looked at load capacity on tasks which are a part of flying skill.

In considering the allocation of more functions to the pilot in an attempt to reduce the avionics costs, past evidence indicates that the pilot can be trained beyond the minimum level so that the information processing time requirements may be reduced somewhat. If a thorough task analysis is made, this can also be used as a basis to help the pilot establish priorities for handling the vast amount of information which he is receiving.

The design of the cockpit and display are not specifically part of a training program. The tasks of the pilot, however, can certainly be easier if careful consideration is given to task requirements, probable sequencing of activities, and "natural" responses, as well as the physical characteristics of the pilot. These should all be part of an integrated design effort.

4.4 COST FACTORS

Although weapon system designers include some limited recognition of the contribution of man in the system, too little recognition has been given to the importance of man in the total life-cycle costs of the system. Engineers, perhaps, have not had the necessary data, but there is a definite effort now being made to fill this gap.

4.4.1 Manpower Costs

There has seemed to be an implicit assumption that there will always be an abundance of people in the military services to operate and maintain a system. Manpower modellers warn that we are approaching a limit. As far as a volunteer force is concerned in peace time, we are faced also with the ever-increasing cost of manpower limiting the size of the force we can afford. In addition, there are factors we cannot control, such as the general economy, which can have a definite impact on the available manpower pool.

4.4.2 Training Costs

Inadequate attention has been given also as to the probable quality of manpower available. As systems become more complex, we have required more qualified technicians to maintain and operate systems, apparently assuming the needed technicians are available or can be trained. Some research has indicated that knowledge of the quality of people available can have an impact on system design[7].

The quantity and quality of people available can have definite impact on training costs. Training would have to be more extensive – and more expensive, probably – if we have lower quality people to operate and maintain a system.

The hopes for reducing the costs of the avionics of a system by decreasing automation and placing more load on the pilot may be more apparent than real over the total life cycle. If the decrease in automation adds greatly to the pilot's workload, man's limitations may require a copilot or overtraining, so that the already high costs of pilot training increase.

It is not the pilot training costs only which must be considered. The cost of training support personnel is also an important, if not the primary factor. There are some questions which must be answered in tradeoff considerations. Will the system be designed so that maintenance is merely removal and replacement of components? Will the design require troubleshooting? The answers to such questions will impact on the kinds of people needed for support and how they must be trained.

If the weapon system design places requirements for extensive training, this reduces the availability of manpower. To obtain maximum benefit from that training, life-cycle costs must include the need for long term retention of trained personnel. This consideration may lead to use of civilian rather than military. If the civilians have already been trained, reduced training costs can help offset possible higher pay requirements.

4.4.3 Equipment Costs

In the cost of automation, not only is there the cost of equipment, but there is once again the cost of support personnel. There will have to be checks on the accuracy of the equipment and people trained to maintain it.

4.5 TRAINING DEVELOPMENTS

4.5.1 Flying Training Research and Development

The information we have gained has not really been integrated to provide a coherent picture of training a superpilot. Smode, Hall, and Meyer in a 1966 report[14], and Prophet[10,11] in 1976 reports, have provided excellent summaries of much of the research on flying training accomplished during the past fifteen or twenty years.

With the arrival on the scene of improved training devices and, particularly, with the ever-increasing capability provided by modern simulators, we are moving toward having greater knowledge and better techniques for training pilots.

One series of studies[8] developed a behavioral taxonomy of undergraduate pilot training tasks and skills and provided some skill comparisons among different tasks, and determination of skill difficulty within and between tasks.

With the use of part-task trainers and full mission simulators, there is the opportunity to teach the basic skills in the most favorable atmosphere of minimum stress. Then as skills are acquired and established the student pilot can be given more stressful situations and some training for emergency situations. Training devices, particularly the simulators, can serve very usefully in continuation or proficiency flying and for a more cost effective periodic recurrent training for those whose skills may have been degraded through period of out-of-the-cockpit assignments[13]. As indicated previously, there have been few satisfactory measures of pilot task loads. Several studies are now underway or projected which may provide more information in this area.

Some efforts also have been made to identify the characteristics of effective fighter pilots and methods of training and evaluation[3,15]. Other research is ongoing to try to establish critical skills and simulator training requirements and effectiveness.

4.5.2 Manpower and Training Requirements Models

We also have better models for predicting manpower and training requirements for new systems in early stages of development. Some of these have been documented in a series of technical reports by Tetmeyer et al.

In addition, we are also establishing better ways of training maintenance personnel, both through improved methods of presenting technical data and through the use of maintenance training simulators and crew trainers.

4.6 RECOMMENDATIONS

Starting with the activity allocation concept, this chapter emphasizes the use of task analysis to review the individual/equipment ratio for successful completion of a task and establishing behavioral objectives in training. Some comparative capabilities of the individual and the machine have been suggested; it is not recommended necessarily that activity be allocated solely on this basis.

The life cycle costs of an aircraft (15-year period) may reach 16–20 million dollars currently. The cost of avionics, in terms of life cycle costs, makes this area a likely one in which cost may be reduced. In figuring costs, however, the personnel costs, a major factor in life cycle costs, must be studied very carefully in any trade-off study.

Before it is possible to make definitive statements about the feasibility of reducing avionics costs by shifting more requirements to the pilot, we need more data in several areas.

One of the areas is that concerned with establishing points of overload. Man's adaptability and versatility, individual differences, and the reluctance of investigators to press man beyond safe limits have made it difficult to obtain measures of the physical, physiological, and psychological limits. Improved instrumentation and techniques offer some hope for better definition of these limits.

One of the long-standing problems in determining training effectiveness is that of objective performance measurement. Again, with technological advances and clearer definition of behavioral objectives, this area can, and should be, pursued more intensively so that there can be better prediction of the successful and unsuccessful.

As a further step, there needs to be greater emphasis on identifying which skills are essential to successful performance. This information can help refine selection and training procedures.

The diversity of ideas and areas of concern are adequate indication that the process of training is interactive with and dependent upon many factors.

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SECTION 3

MISSION ANALYSIS

Section 3

MISSION ANALYSIS

This section contains three chapters dealing with specific aircraft missions.

The first chapter outlines the mission of the variously called Air Superiority, Air Combat or Fighter Aircraft and identifies the problems faced by the pilot in completing a typical scenario. Some guidelines are given for solving the fighter avionics design problems and techniques the cockpit designer can apply in the selection of the appropriate avionics are shown. The chapter also discusses recommendations for future research upon pilot avionics optimisation. For this purpose the mission is divided into phases. Operational Sequence Diagrams, are included to demonstrate the piloting tasks involved in each phase. In the successful execution of his mission the pilot must concentrate upon two problems additional to controlling aircraft viz; threats and targets. Those related to threats are detection, identification, and avoidance. Target problems are detection, identification and destruction. Efficiency may well be improved by a reduction in dependence upon sophisticated avionics through the use of tactics, procedures, training, and increased aircrew size; and by improving the avionics on-board the aircraft with the use of digital computers and a conscious design aim to increase equipment reliability. Methods are offered for the design of the avionics system man-machine interfaces. These attempt to employ the approach suggested by the methodology offered elsewhere in this book. Some new techniques are described, such as computerised models of layout for the design of aircraft cockpits.

The second chapter presents the special considerations applicable to Ground Attack aircraft. A special aspect of this role is the final phase of the attack. This requires considerable study since it is in the last moments, say, a few seconds at low altitude, between the sighting of the target area and the release of the weapon that the pilot or other aircrew must identify the target, acquire it, release the weapon and make an escape manoeuvre. Considerable assistance is needed from avionic and other systems during this operation, but even if this assistance is available the success rate will mostly depend upon the crew ability. That ability will be affected by the presence of the extremely hostile external environment and the need in many cases to fly at high speed close to the ground. Operation Sequence Diagrams are used to illustrate the particular problems for this role. Some of these problems are discussed in general terms and immediate human factor research needs are recommended.

The third aircraft chapter deals with the helicopter and covers avionics system design and human factors which affect the efficiency of the total man-machine system in the helicopter. Until recently effort on helicopters has been directed mostly towards improving the aerodynamics structures and general engineering aspects. In some measure this has been due to the primary role of the helicopter which has been that of an airborne observation platform, or as a means of transporting personnel or materials. More recently however, helicopters have been used as complete weapons systems having their own associated complex avionics. Helicopter performance in terms of speed and load carrying ability has been greatly increased. Now a great deal of time, effort and cost are required to produce a small gain in performance. However, it is expected that further appreciable gains in the overall system effectiveness can be achieved by better use of the human contribution. This contribution is considered in two major areas, cabin environment and the matching of the man/machine interface. With regard to the environment, the aircrew efficiency and therefore the performance of the total system can be severely impaired if the environment is allowed to affect air crew comfort and performance. This may take the form of direct interference with the aircrew task by noise masking of audio signals or by indirect contribution to fatigue. Many of the noise and vibration problems are unique to helicopters and are associated with their rotors and transmissions systems. Some of the effects of the cabin environment, and ways in which it could be improved are offered. Optimising the balance between human capability and system automation is common to both fixed and rotary wing aircraft. For the optimum division of duties between man and equipment to be realised, the system objectives must be stated and the functions required from the system must be analysed in the early stages of the helicopter design. Therefore it is essential that the purpose of the equipment contribution to the total weapon system must be clearly defined and understood by designers and operators. When the design has been completed it may be possible to use simulation methods to endorse or reject the earlier decisions. Interactive simulation studies should enable the final match of equipment to man to be free from major problems and produce a smoother acceptance of the production helicopter weapons system into service.

Section 3

CHAPTER 1

THE DESIGN OF AIR COMBAT AIRCRAFT

1.1 INTRODUCTION

Using FY-70 dollars on which to base the estimate, the cost of a WW II air combat aircraft (P-51) was approximately $100 000. The most sophisticated of air combat aircraft today are nearly 100 times as expensive as the P-51 (Ref.1). Even taking into account the impact of inflation, the increased cost is considerable. Consequently the Western Air Forces are facing a very difficult problem of cost effectiveness.

The effectiveness of an aircraft as a weapon system must be considered since it could be shot down by a relatively cheap surface-to-air missile. To achieve a reduced cost within the constraints of very demanding mission requirements, which tend to add complexity and costs to the aircraft, is difficult. The purpose of this chapter is to suggest various ways in which the crew station designer could reduce avionics complexity and costs, depending upon the mission. The air combat aircraft is taken as an example. Some of the aircraft design and task or mission aspects are described, to familiarise the reader with essential background, before the actual economies are suggested.

Therefore the chapter is organized as follows. Firstly the combat aircraft missions are described. Then some of the associated problems are considered, followed by suggested methods to reduce complexity and cost of the avionics of this type of aircraft. Methods used in the design of the total aircraft system, are discussed subsequently together with the system tradeoffs the designer must face. Conclusions and recommendations for future research are then offered.

1.2 MISSIONS OF THE AIR COMBAT AIRCRAFT

1.2.1 Introduction

The designer of the combat aircraft avionics system and crew station must have some concept of the intended mission. His ideas must be generated in a mission context since the particular mission will put unique constraints on the system, e.g., high "g" forces, not faced in other missions. By understanding the mission the designer can determine which functions to allocate to the pilot and which to automate.

1.2.2 Mission Types

Using United States terminology: Point Intercept, Strike Force Escort, and Combat Air Patrol are the three primary missions for the air combat aircraft. Although the three missions have different objectives, there are many common features among them. The primary objective of the Point Intercept Mission is to attack and destroy enemy offensive aircraft which are attempting to destroy a target located in friendly territory. This usually requires close coordination with a ground-based radar net or with an airborne system such as the Airborne Warning and Control System (AWACS).

The Strike Force Escort, however protects friendly aircraft which are performing ground attack missions. Often this requires deep penetration into enemy territory and the aircrew must be aware of ground-based threats which may not be present in the Point Intercept Mission. Additionally, the Escort Mission requires close coordination with the Strike Force aircraft rather than the ground-based radar net.

The objective of the Combat Air Patrol (CAP) mission is to deny the use of the air space over a given geographical area to the enemy. A second, but equally important CAP objective, is to secure that air space for use by friendly aircraft. This mission may be conducted over friendly territory, over the Forward Edge of the Battle Area (FEBA), or beyond the FEBA over enemy territory.

The following theoretical mission scenario is presented to illustrate typical tasks which the combat aircraft must perform. It should not be viewed as a model, but rather as a very general outline of a mission profile in this case a CAP, in a low to moderate threat environment without benefit of an AWACS and without reference to any specific weapon system. The particular avionics components are also hypothetical. The mission profile is shown in Figure 1.1. It is broken up into the following phases: Ground State, Take-Off, Cruise, Attack, and Land. Operational sequence diagrams, showing the tasks involved in each of these five mission phases, are included as Figure 1.2.

The example represents some of the activities and is not inclusive. Time spent by the designer on pilot task analysis will benefit the total design as solutions to the individual design problems are realised. If the mission is understood, the designer can concentrate on its unique problems and select "worst case" situations.

1.3 RELEVANT FEATURES OF AIR COMBAT AIRCRAFT

1.3.1 Introduction

Some combat aircraft functions are obviously common to all aircraft. For example, landing conditions. Such aspects will not be considered here. The following paragraphs deal with the functions which are unique to the combat aircraft.

1.3.2 Threat Detection

The air combat aircraft will be the target of threats. The most recent Middle East war provided a relatively high threat environment with which the aircraft had to contend[2]. The threats faced by pilots in future conflicts are expected to include both ground-based and airborne. The ground-based threats may consist of surface-to-air missiles (SAMs) and antiaircraft artillery (AAA). Such threats often will be mobile and cover both high and low altitude air space. The airborne threats will include high performance aircraft capable of attacking with both missiles and guns. It is possible for SAMs to be fired in salvo without radar guidance or for SAMs to be optically sighted. In these cases the pilot must detect the missile by seeing it as it is launched. Since typical missile flight times range from 15 to 25 seconds[3], the magnitude of the problem becomes apparent. Threat detection can be more difficult when enemy ground control vector the airborne threats. Threats can thus approach without the use of active aircraft radars until they are in close proximity to the acquisition and launch envelopes of their ground defence missiles. It becomes increasingly difficult as patches of cloud cover obscure the ground.

1.3.3 Threat Identification

Threat identification requires determination of the threat being ground-based or airborne and its radar status (search, lock-on, etc.). The problem is compounded if the threat numbers are increased due to clutter problems.

Clutter can be evident in both the auditory and visual channels. In the former it results in so many warning tones that, coupled with the voice communication, auditory information becomes very difficult to interpret meaningfully; in the latter, the problem arises because so many symbols overlap each other that indistinguishable symbol "blobs" appear on the airborne radar screen.

If the threat priority is selected automatically, tradeoff decisions still remain involving the division between avionics which are allowed to decide threat priorities and the extent to which the pilot looks at the symbology presented and decides his own priorities.

1.3.4 Threat Avoidance

Once the threat is detected, either visually or by some sensor, the pilot must avoid it if the mission is to be completed successfully. The sensor can give the pilot early warning of a missile launch, but visual sighting is also needed if the missile, either air-to-air or surface-to-air, is to be avoided.

Even if an enemy fighter first appears at six o'clock, an early sighting may allow the pilot to turn and/or extend the range to outside the lethal area. Avoidance of surface-to-air missiles (SAMs) also depends on an early visual pickup of the airborne missile. The pilot must watch the missile's flight long enough to determine its characteristics and to plan a manoeuvre that will defeat the missile in its terminal guidance phase. (Reference 4, p.24.)

The concept of defeating the missile in the terminal guidance phase requires a pilot decision as to when he should start his "jinking" manoeuvre, i.e., rapid changes about all three aircraft axes. If he starts the manoeuvre too early, the missile may catch him, and if he starts it too late, he may not be able to avoid the missile no matter what he does.

1.3.5 Target Detection Beyond Visual Range

The targets consist of enemy aircraft, either strike forces or air superiority aircraft, or both. The air combat aircraft must be able to detect hostile aircraft beyond visual range and, ideally, beyond the launch range of their air-to-air missiles or air launched cruise missiles. The problems are then somewhat different from the threat problems just discussed because rather than avoid threats, the pilot must actively seek to destroy the targets. The pilot must pick out real targets from noise generated on the cockpit display, especially under conditions where targets are employing various types of countermeasures, such as chaff, and may be flying at low levels, using the terrain for masking.

1.3.6 Target Detection Within Visual Range

Circumstances can arise which require visual identification of the target. Causes can be the confusion resulting from a great number of aircraft engaging in an air battle or because the rules of engagement demand visual identification. The pilot sometimes needs to acquire the target visually when it is able to launch air to air cruise missiles and may be, when operating under IMC rules, once the missiles are launched. One bomber may carry 10 or 20 cruise missiles, and the most sophisticated air combat aircraft could, at best, destroy only six of these in a single mission[5].

1.3.7 Target Identification

Unlike the threat which becomes identified because it is in an active radar mode, the target may be flying passively. Consequently active interrogation by the air combat aircraft IFF system is necessary to check that the target is not friendly.

1.3.8 Target Destruction

For the case involving multiple targets, it is necessary to assign an importance level or priority to each. Though computer algorithms can allocate target priorities, the pilot must often override this order of priority because of unique circumstances. The information must be presented to the pilot in a simple and concise manner so that he can make the priority decision efficiently. He must also be able to change the priorities and fire the missile at the appropriate target in a relatively short period of time. This is a crucial issue in a single seat combat aircraft since the pilot has only a few seconds available to scan the display for status information[6]. Further reference is made to this topic in the air-to-ground attack aircraft chapter.

1.4 DESIGN PROCESS

An illustration of how aircraft, avionics, and crew station could be designed is now included and arranged according to the over-all man-machine system philosophy discussed in Section 2 Chapter 2. In this example it is assumed that the aircraft mission and scenario are known, the design of the man-machine system is then structured according to the following:

(1) objectives of the system,
(2) functions that the system must perform in order to accomplish the objectives,
(3) various methods of accomplishing each function, and
(4) equipment and procedures, or means, associated with these methods.

1.4.1 The Objectives

The dual objectives of denying the use of a given airspace to the enemy while at the same time making it available for use by friendly strike/attack aircraft imply different requirements for the air combat aircraft. To deny the use of the air space to the enemy requires that the air combat aircraft be able to intercept and attack enemy strike/attack, heavy bomber forces, and accompanying fighter escorts. The second objective making the air space secure for use by friendly strike/attack aircraft requires the air combat aircraft to intercept and destroy enemy fighter aircraft. Since the aircraft must perform both mission objectives, the avionics complement for the aircraft is severely affected. For example, the acquisition of enemy strike forces while they are beyond air-to-surface missile launch range may impose a number of constraints on the design of the target acquisition sensors and associated computer processing requirements; conversely, the engagement of enemy fighter aircraft may impose constraints upon the gun and sighting systems.

1.4.2 The Functions

The functions necessary for the air combat aircraft to perform its mission are also affected significantly by external factors, e.g. the sophistication of the air or ground-based command, control and communication system.

(a) *Internal Functions*

Both existing aircraft and the mission requirements can give clues as to the functions the aircraft should perform, the designer need not be constrained to only what exists currently, but should use current capabilities as a basis for future design. A useful initial step is to make an examination of the technical manuals of existing aircraft. The designer should examine the design of several air combat aircraft, to ensure a broad appreciation of alternative design philosophies. A list can be compiled covering the required functions, similar to the following:

Navigation The aircraft must be able to travel from its home base to the target area and back, and may need to rendezvous with other friendly air combat, strike attack, and tanker aircraft. Diversions are another aspect of the navigation function. Range and altitude requirements, further help define the exact nature of the navigation function.

Communication Communications are of prime importance. There may be requirements to communicate with a variety of stations, including: ground-based and/or airborne command, control, and communication systems; with friendly ground forces; and with other aircraft operating in the same airspace, including other air combat aircraft, tankers, strike/attack, forward air controllers, and search and rescue.

Failure Warning The aircraft must be able to continually monitor its "health" and report to the pilot any serious system malfunctions. Fire detection and engine malfunctions are of prime importance. If the aircraft has an active control flight control system, electrical failures are crucial. This function might include informing the pilot of the remedial steps needed to overcome the failure.

Threat Detection A threat detection function is essential for the air combat aircraft. Invariably some system assistance is needed.

Target Detection Target detection is essential. It may be achieved by direct visual observation or with the assistance of avionic equipment.

Stores Management The design must enable the pilot to select a weapon with minimum delay and change from one kind of weapon to another. A high degree of system reliability is needed.

(b) *Capabilities Outside the Aircraft*

The selection of methods to implement functions within the air combat aircraft depends on the sophistication of system capabilities outside the aircraft which it can utilize. The aircraft could be totally self-contained, but this suggests an extremely sophisticated and costly aircraft with complex avionics. However, it is difficult to conceive a scenario in which the air combat aircraft could depend on no outside capability.

Command, Control and Communication (C3) System This system may be composed of airborne, space and ground-based components. It provides for long range detection of threats, and through its command function can vector air combat aircraft into proper position to meet such threats. The system affects the navigation function since it can direct the aircraft by providing radar vectors or, in conjunction with an auto-pilot, can data link automatic flight commands. This could reduce the need for a sophisticated on-board navigation function. The C3 system also effects communication since it can communicate to the air combat aircraft through data link when voice communication may not be possible. With long range surveillance radars, the C3 system can perform and assist with threat detection and identification.

Threat Suppression Ground based threats can be reduced significantly through the use of threat suppression aircraft. If these aircraft are available, the amount of electronic countermeasures avionics needed aboard the combat aircraft is lessened considerably. For airborne threats the use of electronic warfare aircraft may offload avionics requirements from the combat aircraft.

1.4.3 The Methods

One design approach to determine the method of implementing the required functions is to plan for the "worst case" situation in which the air combat aircraft can depend upon minimum support from outside capabilities. The designer is then able to provide an aircraft which is viable in a high threat-minimum support situation, while allowing the option of changing the on-board avionics complement as more outside capabilities become available. With this overall philosophy in mind, he can then select the methods the aircraft will utilize to fulfill its functions.

Navigation In the "worst case" the AC aircraft must be able to navigate in adverse weather without external navigation aids. This implies that the method must provide for self-contained and jam free operation. Such constraints limit the primary method of navigation to an inertial or Doppler/Inertial system. In providing for the case of minimum outside assistance, the designer may include TACAN, VOR, and ILS. A data link receiver-flight director may be included to enable the aircraft to function in a jamming environment.

Communications Since voice communication is very difficult in the jamming environment, an alternative method of communication is required. One candidate is data link, requiring the inclusion of a data link transmitter/receiver. In the case of a moderate jamming environment, a high frequency radio is an appropriate method for communication and, finally, in the no jam environment, ultra high frequency or very high frequency radios are usual.

Failure Warning The primary system comprises a combination of warning lights and auditory tones or messages. The methods of monitoring aircraft "health" range from simple displayed sensors to sophisticated sensors feeding central processors and multifunction displays.

Threat Detection and Identification Radar is one method of performing a self contained function. As the amount of outside support increases, the range of the self-contained radar can decrease.

If the aircraft cannot depend on outside support, it must possess an ability to interrogate other aircraft in order to identify them. The method for performing this task is the identification friend or foe (IFF) component of the IFF-SIF set. Conversely, the air combat aircraft must identify itself to other friendly aircraft, and the selective identification feature (SIF) component is used for this. With the use of outside capabilities, dependence on the IFF-SIF radio is decreased.

Stores Management This includes selection, arming, and firing weapons. A simple method of weapon selection requires switches from a stores control panel to weapons stations. Weapon arming and firing can also be accomplished through separate switches. Multi-purpose control panels and switches attached to weapon stations through central processors and multiplex data busses can be used also.

1.4.4 Means

The designer must decide using various criteria, which of several manufacturers' equipment to purchase.

(a) *Cockpit Dimensions*

The cockpit dimensions of different aircraft vary by as much as a factor of 1.5. The dimensions may pose a serious constraint to the designer, and it is crucial that he determine, early in the design process, the minimum cockpit dimensions with which he must contend. Although the limit of reach by the operator automatically sets a dimension limit. A great deal may be known about the critical cockpit dimensions relatively early in the design of the aircraft because of the aerodynamic design considerations.

(b) *The Selection of Automatic or Manual Operation*

The following extracts from Reference 7, pp.92-95, give some general guidance in designs in the selection process.

Tasks in which Computers Excel Men

(1) The performance of many individually easy information handling tasks, time after time and without error, is not at all easy for men – it is what computers do best. Consequently, any high volume information processing task in which the rules for processing are simple and easy is just right for machine performance.

(2) Another task in which computers excel men is long-term storage. They remember immense amounts of information and can reproduce it extremely accurately. . . .

Tasks in which Men Excel Computers

(1) Many computer experts agree that the most important respect in which men excel computers is in the *accessibility of the items in storage*. Men can get at a single memory in many different ways; in particular, they can recover memories on the basis of similarity alone. Computers, by contrast, have no such efficient cross-indexing.

(2) . . . Psychologists and computer experts would also list *pattern recognition*, particularly visual pattern recognition, as an important capability in which men far excel computers.

(3) . . . A major virtue of men is that they have a *high tolerance for ambiguity, vagueness, and uncertainty*. Men are able to detect what other men mean through the smog of what they say, and they customarily do so and behave accordingly. Such tolerance for ambiguity is based on a life-long history of experience with ambiguity and on the ability to argue by analogy from one's own purposes to those of other people. Neither of these characteristics seem likely to be available for computers in the near future.

(4) . . . One reason why men are good at tolerating and exploiting ambiguity is that they can effectively *translate uncertainty into probability* – another task in which men far excel computers.

Using these general guidelines and anthropometric data (see Section 2, Chapter 1) the designer should be able to decide which functions require automation, and to what degree.

(c) *Integrated or Dedicated Equipment Selection*

Integrated equipment offers potential benefits including cost reduction and higher system reliability, however added design and development complexities are introduced and consideration of such technology must be treated with caution.

Three useful considerations are:

(1) urgency of use
(2) criticality of use, and
(3) frequency of use.

Each piece of equipment can be rated on each of these criteria, and from the overall rating, decisions made as to the kind of equipment needed. A typical method for these three criteria is shown in Table 1.1, and described in Reference 7, p.16.

TABLE 1.1

Criteria Rating Categories

Urgency	*Criticality*	*Frequency*
1. Immediate	1. Vital	1. Frequent
2. ASAP*	2. Important	2. Occasional
3. Convenient	3. Useful	3. Periodic
4. N/A**	4. Possibly Useful	4. Infrequent
	5. N/A	5. Rare
		6. N/A

* As soon as possible ** Not applicable

(d) *Equipment Selection*

Cost One major purpose of this paper is to consider ways of reducing cost of modern aircraft through the reduction of avionics complexity – therefore, the cost of alternative equipments should be a major criterion.

Reliability The relationship between reliability and cost can take a variety of forms. Sometimes the simpler and lowest cost equipment may be the most reliable. However, it may be that the cheapest equipment has the greatest life cycle cost because of low reliability. Equipment reliability however contributes to the total system reliability. If a particular piece of equipment fails, the overall system configuration may be such that the aircraft can still perform its mission.

Maintainability The cost of maintaining sophisticated avionics can be very high both in terms of the equipment needed and training of the personnel. New training procedures[8] and new equipments are being introduced already to alleviate these problems. One approach is to place the sophistication into the aerospace ground equipment, so that it can locate the fault at the line replaceable unit level and, in some cases, at the component level within the unit. The equipment designer therefore must know the intended location of his equipment within the aircraft for environmental and for servicing reasons.

(e) *Cockpit Space Allocation*

Methods have been devised for the proper allocation of cockpit space to equipment on an objective basis. These are of particular importance to combat aircraft design. The procedure allocates space to each equipment based on criticality and frequency criteria as previously discussed. The amount of information for display to the pilot is another important factor which should include anthropometric considerations.

(f) *Cockpit Layout*

Having the mission requirements in mind an initial paper layout is made. Models of the anthropometric characteristics of the pilot, this is then modified using a crew station geometry, equipment location, and associated equipment procedures. Through an iterative technique any major faults connected with the cockpit layout can be eliminated before mock-ups are built. Following this analysis cockpit mock-ups and simulators can be constructed to explore the practicability of the proposed design.

(g) *Pilot Procedures*

Each equipment tends to be designed in isolation and operation of such individual units may be relatively simple. However, when all the equipment is placed in the cockpit, the total operational load may be too great. A very detailed time line analysis of the mission can be constructed to show the total pilot workload during each segment of the mission. The amount of time available to complete the task as determined from the mission analysis and the amount of time it actually takes the pilot to complete the tasks are compared. Where the actual time needed to complete the tasks exceeds the time available, an overload occurs.

The following options are then available:

(1) reallocate some tasks to a mission segment where surplus time is available if the mission scenario will allow

(2) provide some additional training to the pilot so that he can complete tasks faster, and

(3) change the design of the equipment or select new equipment which has simpler procedures associated with it. This illustrates the premise that the tasks, needed to operate the equipment are a criterion which should be considered in equipment selection.

(h) *Operability*

So far the design will have been confined to paper studies and arrangments. Inexpensive mock-ups can check pilot reach and vision envelopes, additionally pilot acceptance of the basic cockpit layout can be determined with the aid of checklists which require a subject to reach for each location, probably using a cardboard replica. Errors in cockpit layout can be corrected at this stage at minimum cost.

The next stage is to employ a ground based dynamic simulator, this will allow a more realistic assessment of the total system and its operation.

1.5 SYSTEM CAPABILITY TRADE-OFF

Once the aircraft has been designed, the avionics costs may still be excessive. The designer is then faced with the job of either simplifying or eliminating avionics in order to reduce costs. The designer must weigh a series of system capability trade-offs, as it is of no value to build a low cost, simple aircraft which cannot perform its mission effectively. For the AC aircraft, the European scenario for the 1980s is a difficult mission in a high threat environment. Any reduction in avionics sophistication and, consequently, cost must be weighed against these rather severe constraints.

1.6 CONCLUSIONS

It is possible to reduce avionics costs through reduction of mission requirements, use of special tactics and force mixes, increased pilot training, improvement of aircraft aerodynamic qualities, offloading of avionics to external sources, or addition of more crew members. These techniques have been used in the past and are feasible. The means of cost reduction which appears to offer the most promise is the use of modular, digital avionics. As was stated earlier in this chapter, because of their low life cycle cost and inherent reliability, digitial avionics are very attractive for future aircraft. But it may be that the retrofit flexibility provided by these digital components will be the most important factor. It does not appear that mission requirements are decreasing, but conversely, they seem to be increasing. These increasing mission requirements require a tremendous flexibility on the part of AC aircraft avionics, and digital avionics are the means of providing the required flexibility within some reasonable cost constraints.

1.7 RECOMMENDATIONS FOR FUTURE RESEARCH

Areas for future research are discussed below.

1.7.1 Improve Visual Target/Threat Detection

Although sophisticated IFF systems are carried aboard AC aircraft, situations can arise where visual identification of targets/threats is necessary. During these conditions it is crucial to sight the hostile aircraft as far away as possible; therefore, effots must be initiated to extend the pilot's visual detection capability. One suggested area for future research is the use of long range television or infrared cameras to extend the pilot's visual range by several orders of magnitude. Parameters to be examined include such things as camera range, field of view, and shades of gray (dynamic range).

A second research area related to visual target/threat detection is the use of cueing boxes, circles, etc. to help the pilot locate a sensor-detected target beyond visual range. For example, the AC aircraft radar may have a range of 50 miles, but the range of visual sensors may only be 10 miles. The usefulness of cues to direct the pilot's search to a small portion of the display, until the target comes into visual range, should be investigated.

1.7.2 Improve Visual Target/Threat Identification

One of the biggest problems faced by the AC pilot is the identification of the type of threat after it has been detected. This is especially difficult because the threat may be seen in various attitudes, many of which create visual illusions and distortions to the pilot. Aids are needed to improve the pilot's ability to recognize targets/threats in unusual attitudes. One possible approach is to show the pilot slides of threat/target aircraft at various combinations of attitudes and ranges. A tachistoscope could be used in conjunction with the slide projector to limit the pilot's viewing time. Parameters to be examined inlclude viewing times, ranges, aircraft type and attitudes.

1.7.3 Improve Threat Avoidance Capability

The result of the final stages of air to air engagements is often determined by the pilot's ability to maneuver his aircraft. Maneuverability is the key to both avoiding the enemy's missiles and guns and to getting into his "six o'clock" position. The key to maneuverability is the proper use of the AC aircraft energy. The design of an optimized display of the energy state of the aircraft is in its infancy. A great deal more work is needed in this area. Parameters to be investigated are methods of displaying Ps, maximum corner velocity, maximum sustained turn rate, and an indication to the pilot as to how to obtain various energy parameters.

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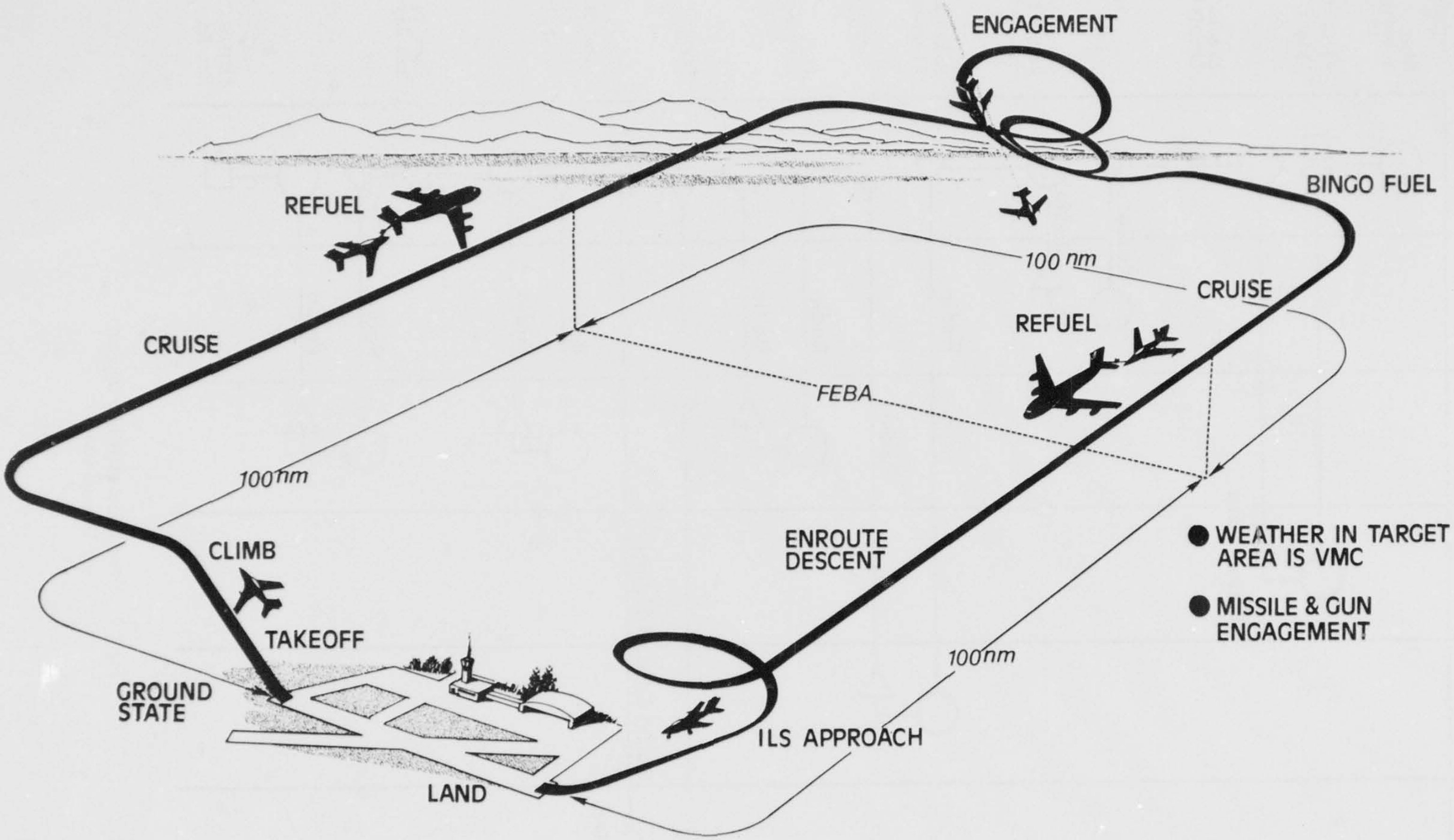


Fig.1.1 Combat air patrol mission

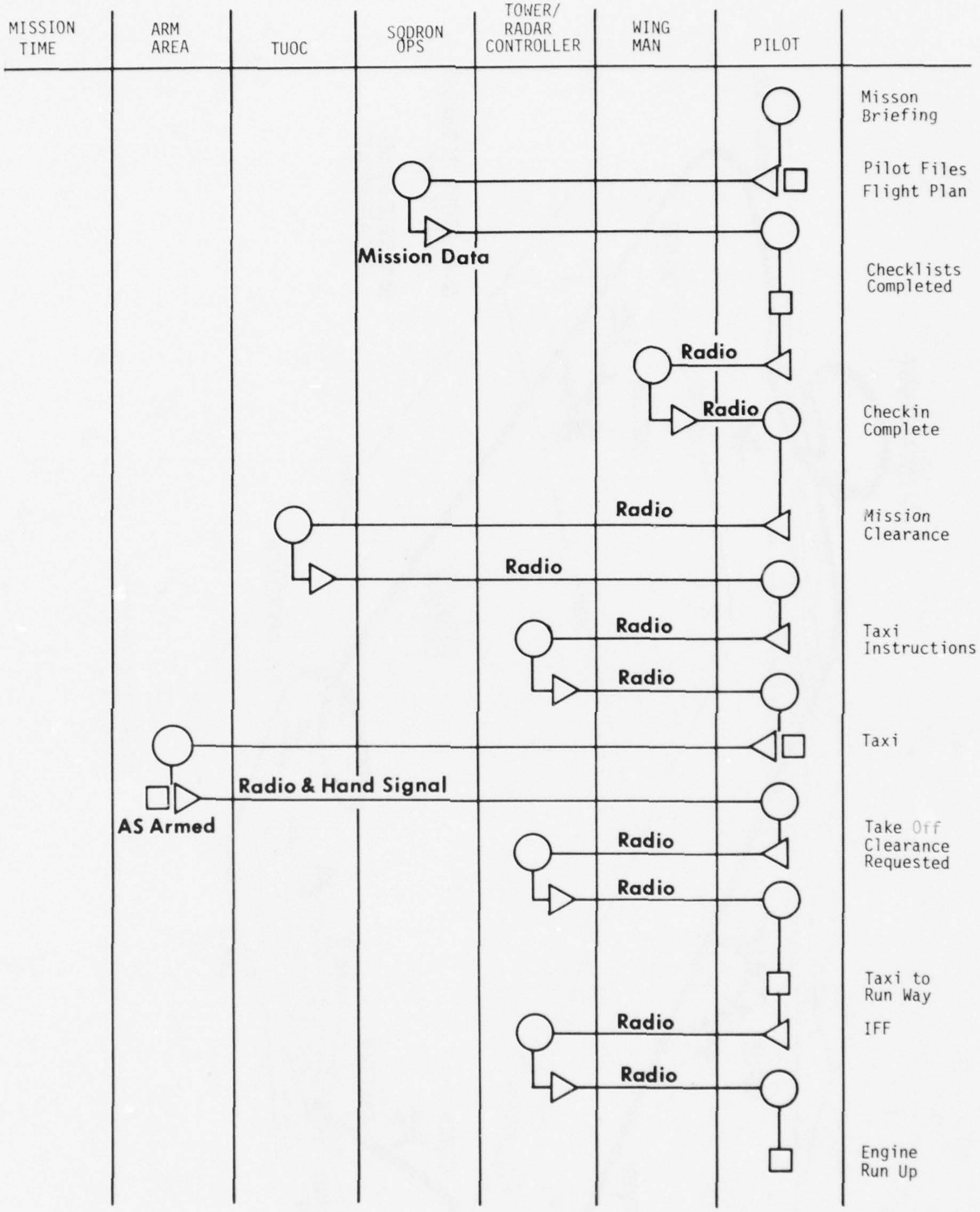


Fig.1.2 Operational sequence diagrams
(a) Ground state

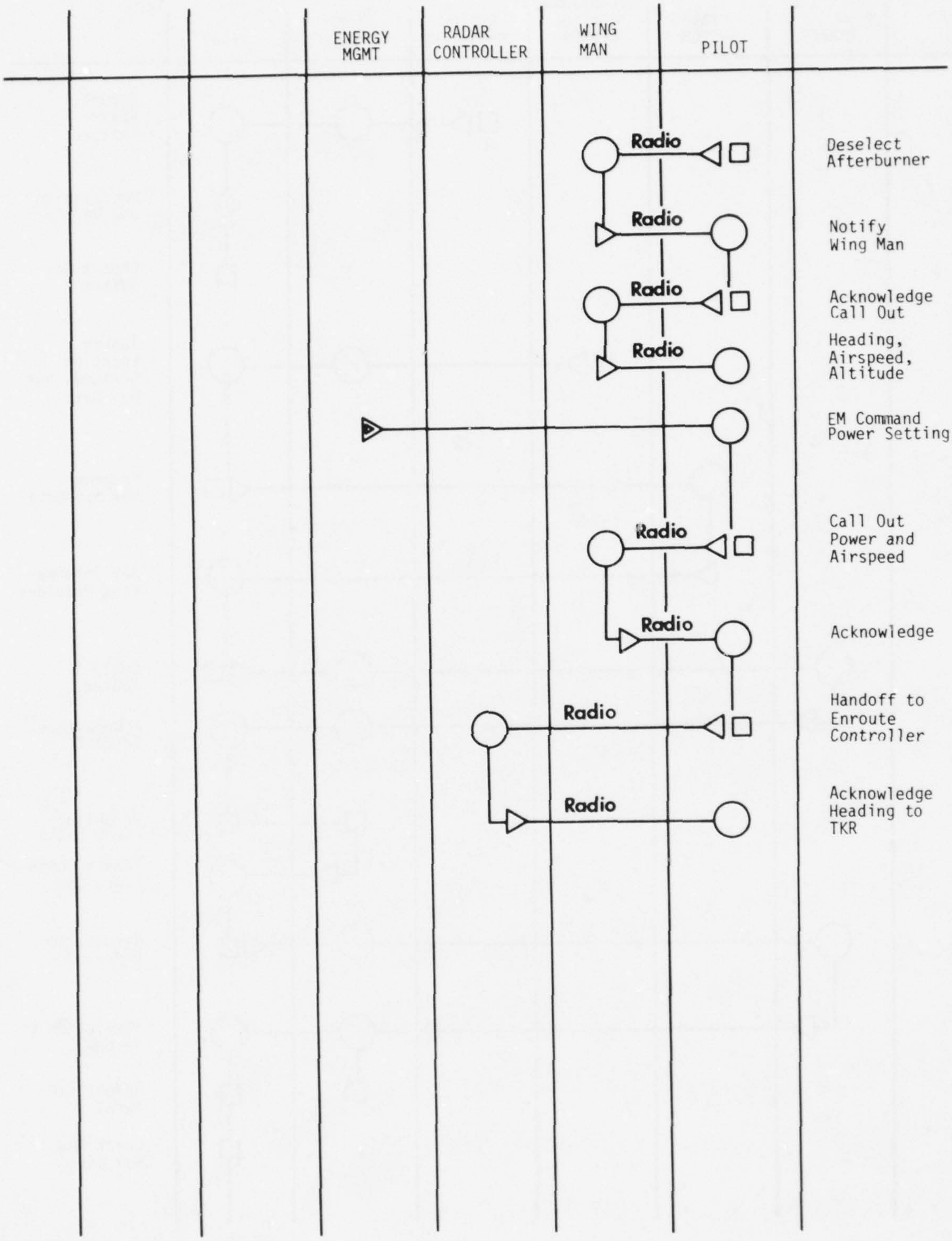


Fig.1.2 (b) Take-off

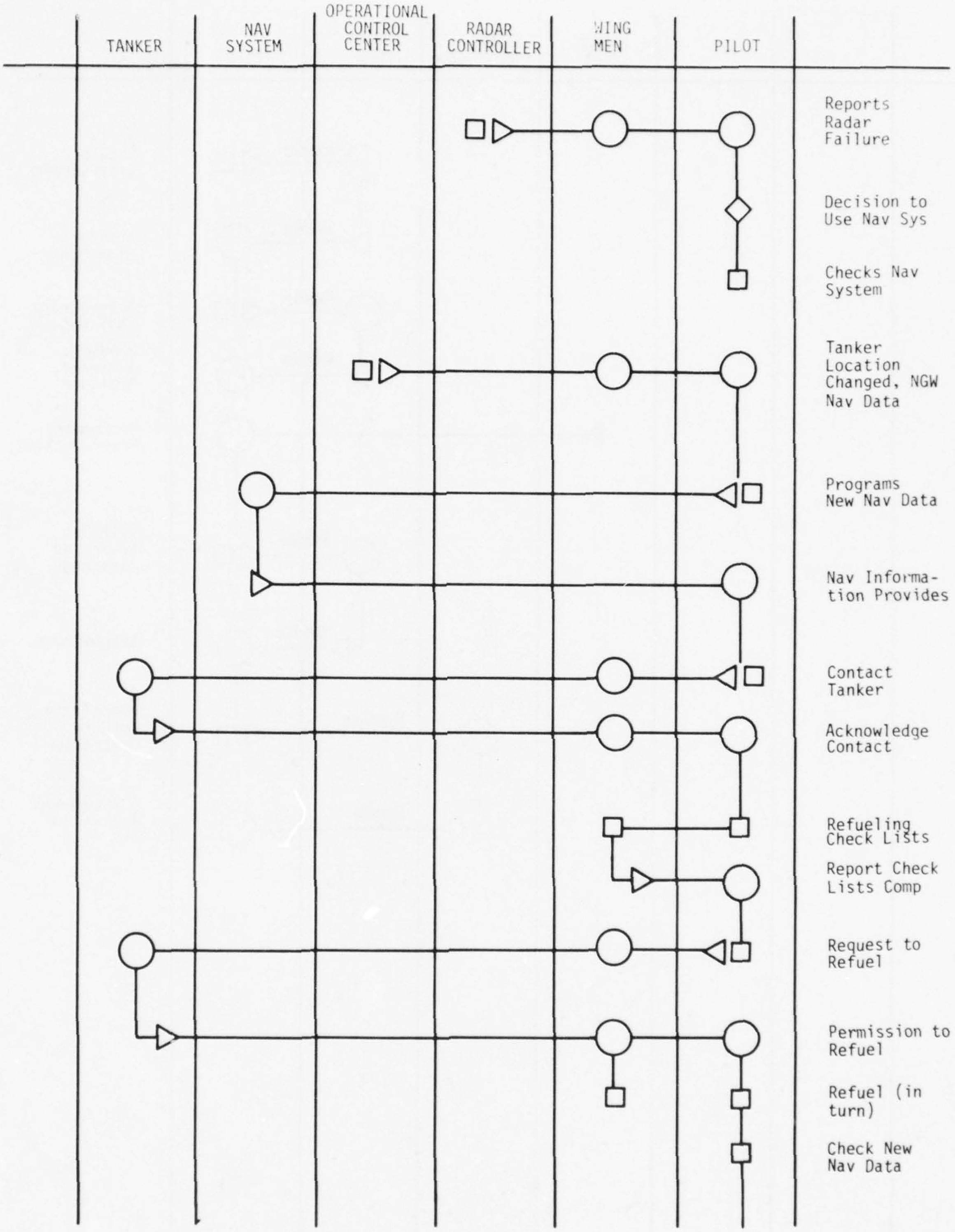


Fig.1.2 (c) Cruise

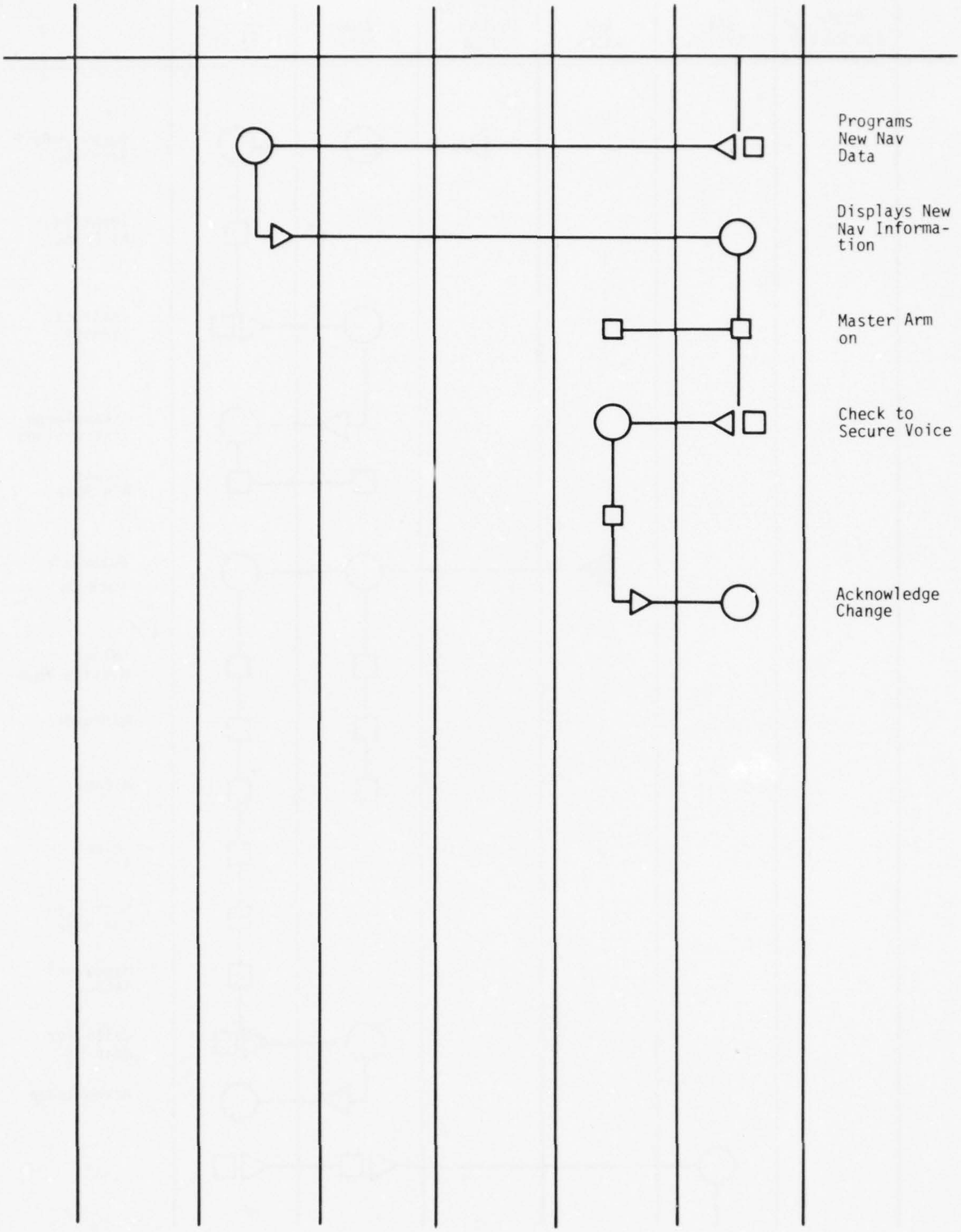


Fig.1.2 (c) cont. Cruise

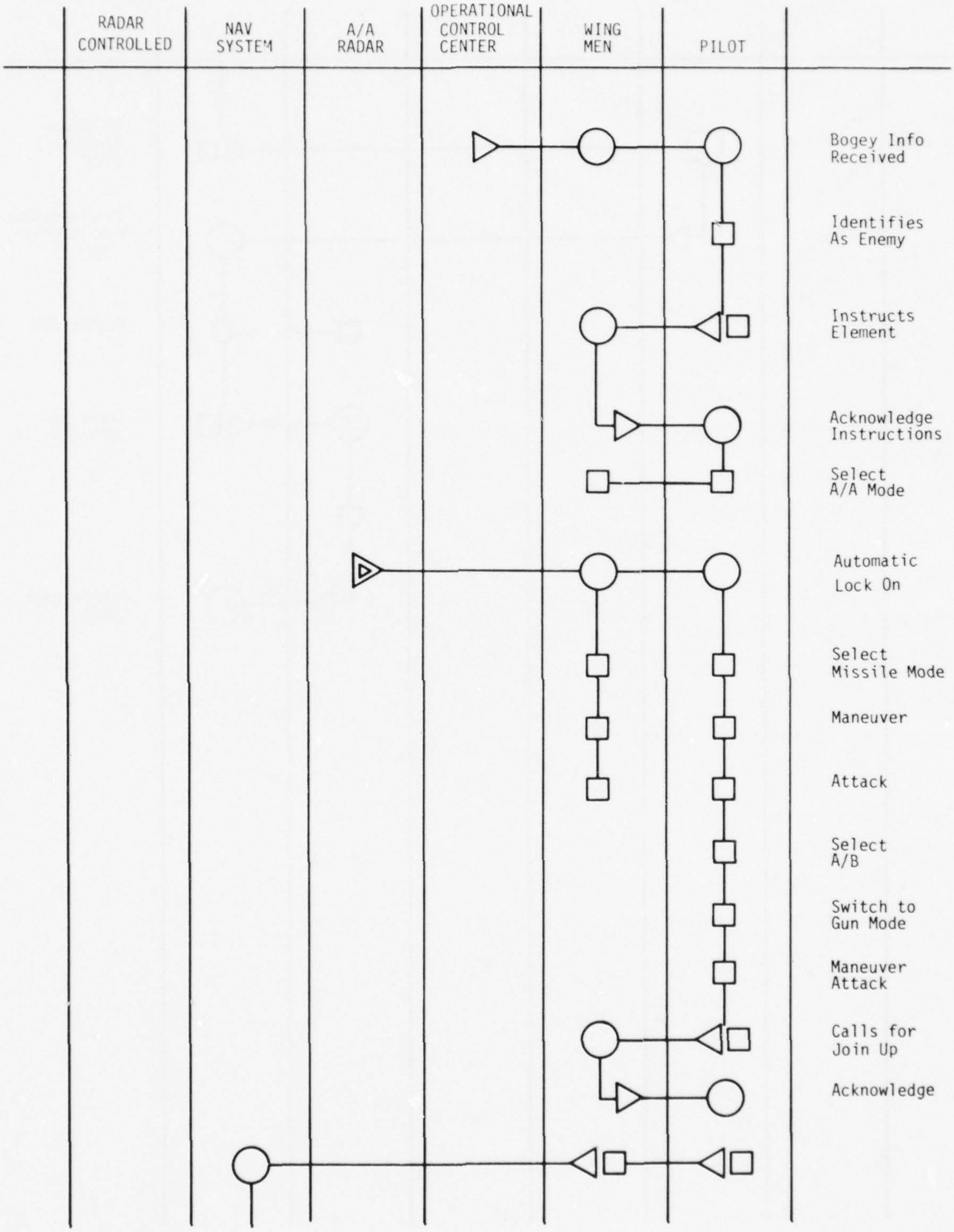


Fig.1.2 (d) Attack

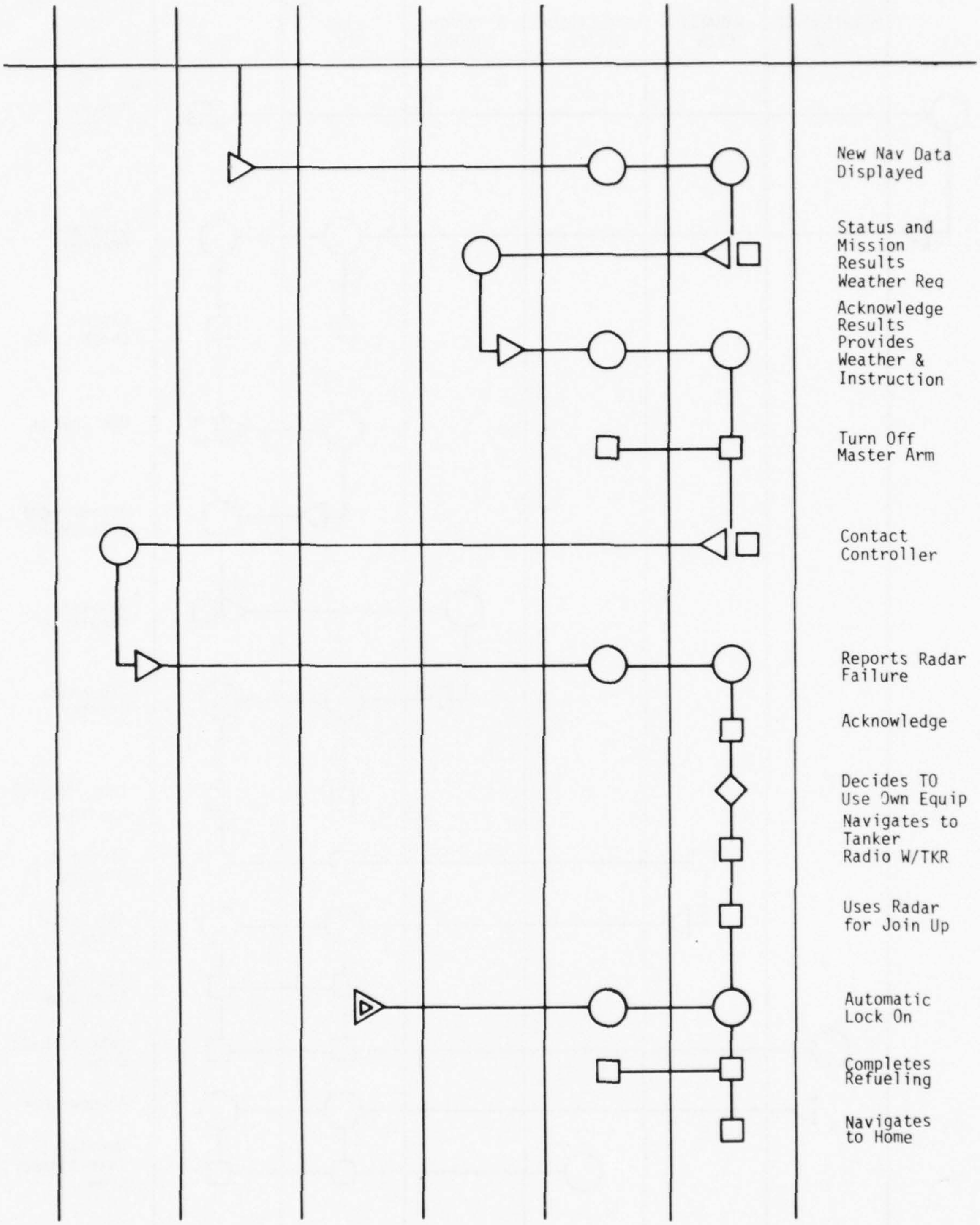


Fig.1.2 (e) Cruise

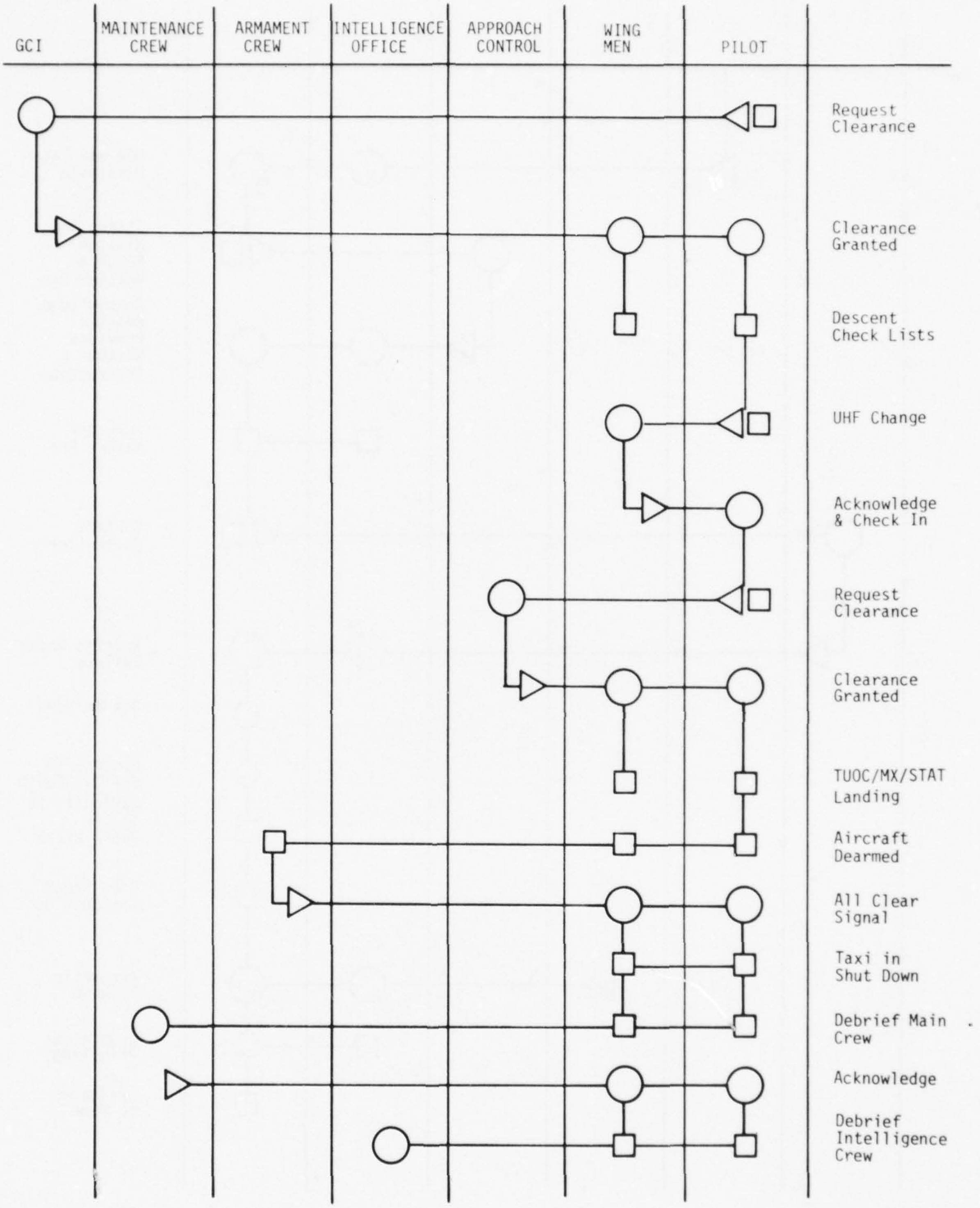

GCI
MAINTENANCE CREW
ARMAMENT CREW
INTELLIGENCE OFFICE
APPROACH CONTROL
WING MEN
PILOT
Request Clearance
Clearance Granted
Descent Check Lists
UHF Change
Acknowledge & Check In
Request Clearance
Clearance Granted
TUOC/MX/STAT Landing
Aircraft Dearmed
All Clear Signal
Taxi in Shut Down
Debrief Main Crew
Acknowledge
Debrief Intelligence Crew

Fig.1.2 (f) Land

Section 3

CHAPTER 2

GROUND ATTACK

2.1 GENERAL

There is a considerable degree of commonality in the human factors aspects of air to ground weapon aiming and those concerned with the air combat aircraft in certain phases of flight. The take-off, climb, refuelling and landing modes are essentially the same. Many aspects of pilot briefing will also be common for both types of aircraft. This chapter will deal therefore with items peculiar to the ground attack mission and the common elements will be regarded as the same as those covered in Chapter 1 for the air combat aircraft.

2.2 SYSTEM DESIGN CONSIDERATIONS

2.2.1 Pilot Workload

In considering the interaction between system complexity and pilot workload in a future ground attack aircraft, a first consideration is that the freedom of choice between system complexity and increased pilot workload is very restricted, since there is only a limited number of things that a man can do well in this role particularly. Options include:

Target recognition.

Identification of live as opposed to dead targets; though it is possible that avionic sensors would be of assistance in this respect.

Selections among multiple targets in typical tactical situations such as targets placed or moving along roads.

Assessment of counter activity.

2.2.2 Machine Tasks

There are some tasks however which machines can do well, particularly those which require computation or calculation. It is well known that a man finds it difficult to calculate when airborne, particularly if he is engaged in another task such as piloting an aircraft. Broad fields of activity best left to machine include:

Navigation.

Weapon Release Point information including "ballistics" calculation.

Improvement of night or poor weather vision.

Storage of positional information for a second pass attack or for photo-reconnaissance purposes.

2.2.3 System Complexity

There are also areas where only an increase in system complexity can lead to any increase in effectiveness, and no amount of workload reduction can improve the pilot's performance.

The pilot workload/system complexity allocation question might be assisted by a consideration of the problem in terms of "Processing Limitations" as suggested by D.A.Norman and D.G.Bobrow "On Data-Limited and Resource-Limited Processes" Cognitive Psychology 7 44-64 1975. This paper draws the distinction between the two limitations of available data and available processing effort.

Resource-Limited Processes. Up to some limit, performance can be expected to be related to the amount of resources (such as psychological effort) exerted to the task. If too little of some processing resource is applied (perhaps because processing resources are limited by competition from other tasks being performed at the same time) then poor performance could be expected. As more and more resources are applied to the task presumably better and better performance would result, within limits.

Data-Limited Processes. Once all the processing that can be done has been completed, performance is dependent solely on the quality of the data. Increasing the allocation of processing resources can have no further effect on performance. Whenever performance is independent of processing resources, we say that the task is data-limited.

It has been argued that all processes have areas in which they suffer from either resource or data limitations. Many processes are either data or resource limited, but others are changed from one to the other by increased or decreased resource allocation.

Task Analysis. Similar concepts can be used to analyse system complexity or the pilot's tasks. Two examples are:

Navigation – the pilot is resource limited, as he could do the job if given enough time to complete it.

Night and Poor Weather – the pilot is data-limited in that he does not have the quality of data without aiding of some sort to permit him to fly as the operational flight regime requires.

2.2.4 Resource Utilisation

From the pilot's standpoint two possible areas of research arise:

(1) To define those aircrew tasks which at present are resource-limited in terms of required performance and to conduct experiments to determine just how little system complexity increase would turn resource-limited tasks into data-limited tasks.

(2) To define the current utilisation of pilot resources, e.g. does he spend time uselessly trying to get information from displays which are resource limited, and can he be trained to allocate his resources more effectively.

2.3 MISSION REQUIREMENTS

Operational sequence diagrams which have particular relevance to ground attack missions are included as Figures 2.1, 2.2 and 2.3 at the end of this chapter.

2.3.1 Task Allocations

Some areas of activity require judgement or experiment to determine whether or not the task should be given to man, left to a machine, or performed by a man with suitable assistance. Typical areas include:

(1) Target filtering, i.e. the selection of likely targets from several possible targets by thermal or other means.

(2) The selection of automatic weapon aiming methods as opposed to manual aiming assisted by some simple aids.

(3) Limitation of low flying capability to either manual terrain avoidance, with an acceptable pilot workload and fatigue problem, or the acceptance of costly systems to perform the terrain following or terrain avoidance task. Given sufficient cues and training it is known that pilots can fly very low safely and efficiently, though only in acceptable weather limits. Considerable experience in World War II proved that so long as weather conditions were not too severe, fairly long sorties could be achieved at heights between 50 and 200 ft over parts of Europe which are fairly flat, at speeds in the order of 250 knots. Unaided manual flying was normal in these circumstances.

2.3.2 Man-machine Interfaces

The whole area of pilot/machine-function allocation appears to revolve around the "Tailoring" of the man/machine interface. The man/machine interactive situation is one where a large proportion of the little research done so far has been highly specific and does not permit the extraction of basic man/machine interface design principles. It would be valuable if a general method of Task Analysis was agreed, for it is only by detailed specification of aircrew tasks in terms of data input/necessary actions and feedback provided that man/machine design principles (once derived) can be adequately applied.

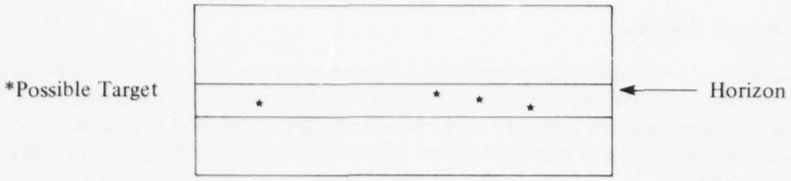
2.4 PROBLEM AREAS

2.4.1 Weapon Delivery

A severe problem is set by the difficulty of target location and identification, particularly to the single set pilot. An area scan must be made and likely targets identified in a very few seconds, generally about 8, if the aircraft is flying at 200 ft or so above the ground.

At low level high speed, the target identification, weapon aiming and store selection must be completed while the target remains in the middle distance. If a rectangular display is available in either a 'head up' or 'head down' configuration, then the critical area containing the targets at this selection phase time 't' is contained in a narrow middle strip formed by the horizon and the weapon release marker as shown overleaf.

The target will not appear above the horizon though it is available as a cue, to give a measure of scale to the scenario, and as a reference.



As the targets appear below the rectangle they can be identified more positively, if the aircraft continues along the same track as at time 't'. At this later time however the decision to release the weapon will have been made. In any case an escape manoeuvre will have been attempted to avoid retaliation by the ground target defences.

It becomes a priority task on the part of aircrew at time 't' therefore to identify the target positively and rapidly and to mark it, lock the aiming system to it and fire. Aids which can assist this process will be useful but only if they can meet these criteria.

Options include the increase of avoinic system complexity to provide:

(1) Automatic flight – to reduce the pilot workload to an acceptable level.
(2) Automatic aiming – once the target is identified.
(3) Automatic cueing.

All of these aids, if automatic, will be costly and very complex.

If targets are to be attacked in groups with the attacking aircraft making a single pass only, the complex solution, though accurate, might well offer a multiple self-targeting weapon. The simpler solution, which relies heavily on the pilot or other aircrew, might employ a single area weapon, which, though covering the target area may not have an acceptably high weight/effectiveness ratio.

2.4.2 Avoidance of Enemy Defences

Options exist which provide for automatic warning of missile threat or the provision of sufficient field of view to give the pilot a degree of protection using visual means. This is not a very satisfactory solution at present but it is conceivable that a high state of training coupled with some very simple but highly obvious optical visual aids may provide adequate protection, at least in some circumstances.

2.5 FRUITFUL AREAS OF STUDY

2.5.1 Weapon Aiming Systems

The pilot/system interface must be optimised to provide natural pilot actions whenever he makes an input to systems and when he receives data from them. Experience points to the need for improvement in the control of air to ground weapon aiming systems. Often preference is given to the Continuously Computed Impact Point (CCIP) method of aiming rather than the Continuously Computed Release Point (CCRP) method. A study of the reasons of this preference would be valuable.

2.5.2 Target Tracking

The ability to track targets without constraining the path of the aircraft would be a valuable option using agile guided bombs or missiles with auto-lock designators. These solutions are complex and costly however. Experience indicates that a helmet sighting system can be used for target designation. One alternative is the use of a Head Up Display (HUD) employing a marker. Such an installation may be cheaper and accurate but with less field of view.

Another option is to slew the aircraft using automatic flight control so that the bore-sight is aligned with the target for weapon release. The aircraft returns to its original heading after release, the flight path vector however remaining unchanged throughout the aiming and release operation. Such a technique is viable only if a very wide field of view is available to the sensor and display in the aircraft. This is a form of control configuration and is likely to introduce a significant degree of system complexity to the aircraft.

2.5.3 Gun Sights

Tracer type gun sights may be designed to give assistance in aiming off the target to allow for time of flight of the bullets and the manoeuvres of both target and attacker. The information is displayed on the HUD.

2.5.4 Manual or Automatic Systems

The potential accuracy of weapon aiming systems is closely related to the associated pilot workload. Pilot-induced oscillations can result during target tracking if the velocity vector lags his control of the target marker. Difficulty can be experienced in keeping the target markers over the target. Kinematic ranging requires tracing the target for several seconds, this introduces a preference for manual rather than automatic release, which is generally less accurate. Further human factor studies are needed.

2.6 FURTHER DESIGN CONSIDERATIONS

All the examples quoted above point to the workload advantages of using the "natural" method that the pilot uses for exchanging information. He does not find it easy to operate the aircraft controls with, say, the right hand while making complex control movements with the left hand completely dissociated from the piloting task. The penalty means extra systems and computing complexity however.

2.6.1 Target Designation

A natural way of designating a target on the face of a Cathode Ray Tube CRT has not yet been found. A natural method of designation could be to place a finger on the target image, though this may be impracticable under conditions of high 'g'. Marking of the image, even on a CRT, with the aid of a helmet sight may be possible. This subject is considered one requiring further study to determine the human limitations.

2.6.2 Target Acquisition

Air to ground attacks in many instances must be made at low level. This is necessary for protection. The geometry of the situation causes the target to appear over the horizon only a few kilometres ahead at the most, with no more than 5–8 seconds of flight time during which the pilot must identify the target, arm his weapons, set himself up for the attack by turning into the capture angle for his missile, designate the target, feed it into the Nav/Attack system and in some cases release the weapon. A fast moving target sight line may also have a high slew rate. A high kill probability can be achieved only if the pilot can achieve these requirements accurately and with one try per function. The alternative is to provide complex avionics which may still prove ineffective without the application of excellent judgment, target recognition and tactical flexibility offered by the human operator. It is difficult at this stage to define precisely a research programme which can improve the human ability in this role but there is much to be gained if improvements can be made. The tasks fall broadly therefore into two types, firstly, the search, identification and designation of targets, and secondly, the control of the priority function of flying the aircraft while performing these, or some of these, tasks. Much could be achieved from research using simulators, but it will be necessary to include the consideration of all facets of the subject in these stages.

2.6.3 Displays

During attack, the single seat pilot will be required to concentrate upon the target acquisition, weapon release and then the escape manoeuvre. Most of his attention will be directed outside the aircraft and attention to Head Down Displays and controls will be very limited, if not impossible. There would appear to be little value in cluttering his Head Up Displays with information which will either distract him or be ignored. Work has been done to improve the guidelines offered to the system designers in this respect but more guidance is needed. If symbology is to be disregarded, then its presentation on the HUD or Helmet Display is irrelevant and the system could therefore be reduced in complexity beneficially.

2.6.4 Warnings

A feature of modern aircraft is the increasing trend to provide system and threat warnings which in some circumstances will confuse the pilot if multiple faults occur, if false alarms are produced, or if damage is experienced. They will then be ignored in many instances since workload may be high. Research has been conducted to improve warning system design but some rationalisation of research results is needed. Alternatives to aural and visual warnings may be needed and it is recommended that they are investigated further. The maximum number of warnings to which a human can react correctly, and quickly, requires assessment since this will influence considerably both the air to ground and the air combat aircraft systems design.

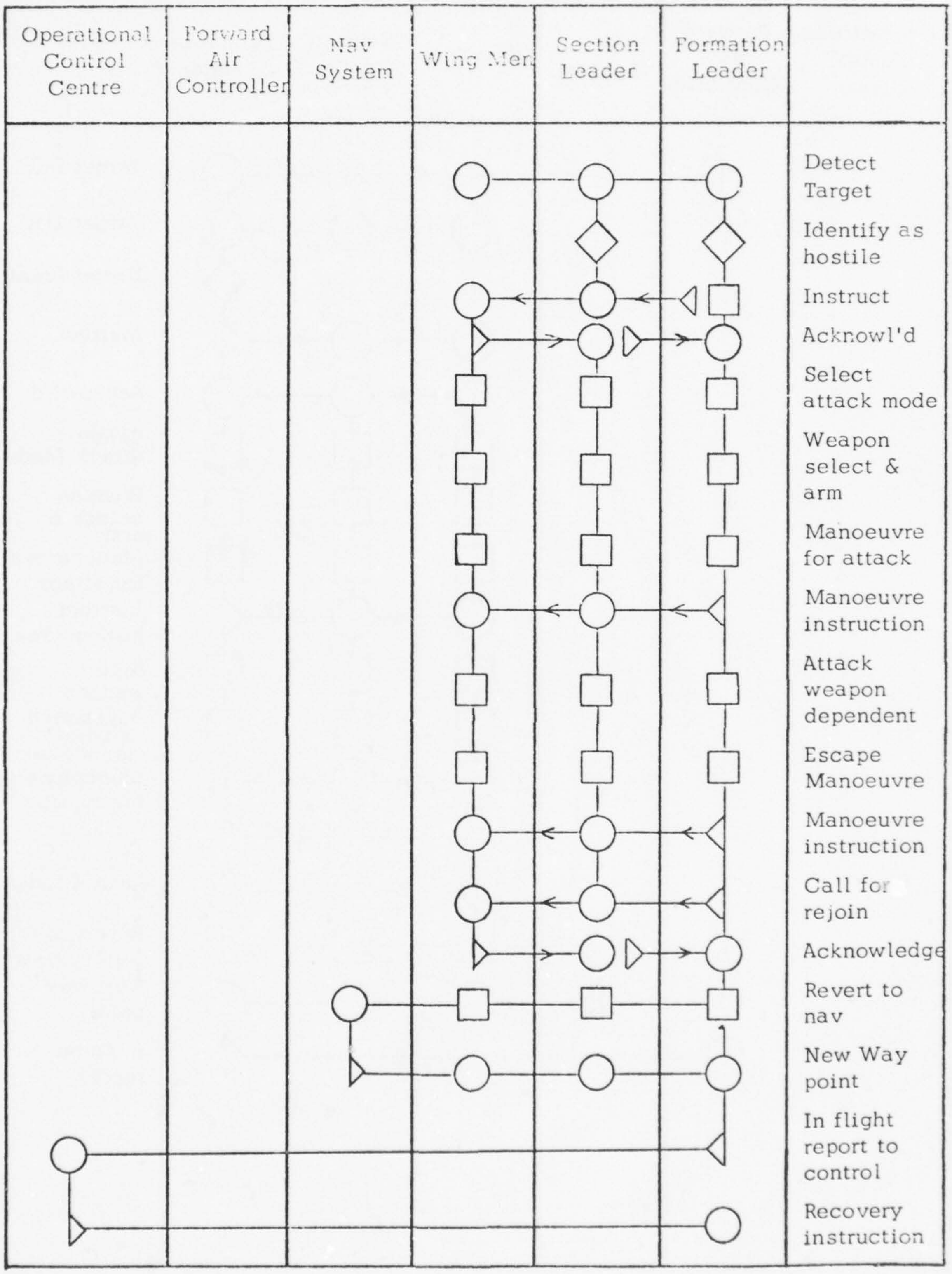


Fig.2.1 Target of opportunity

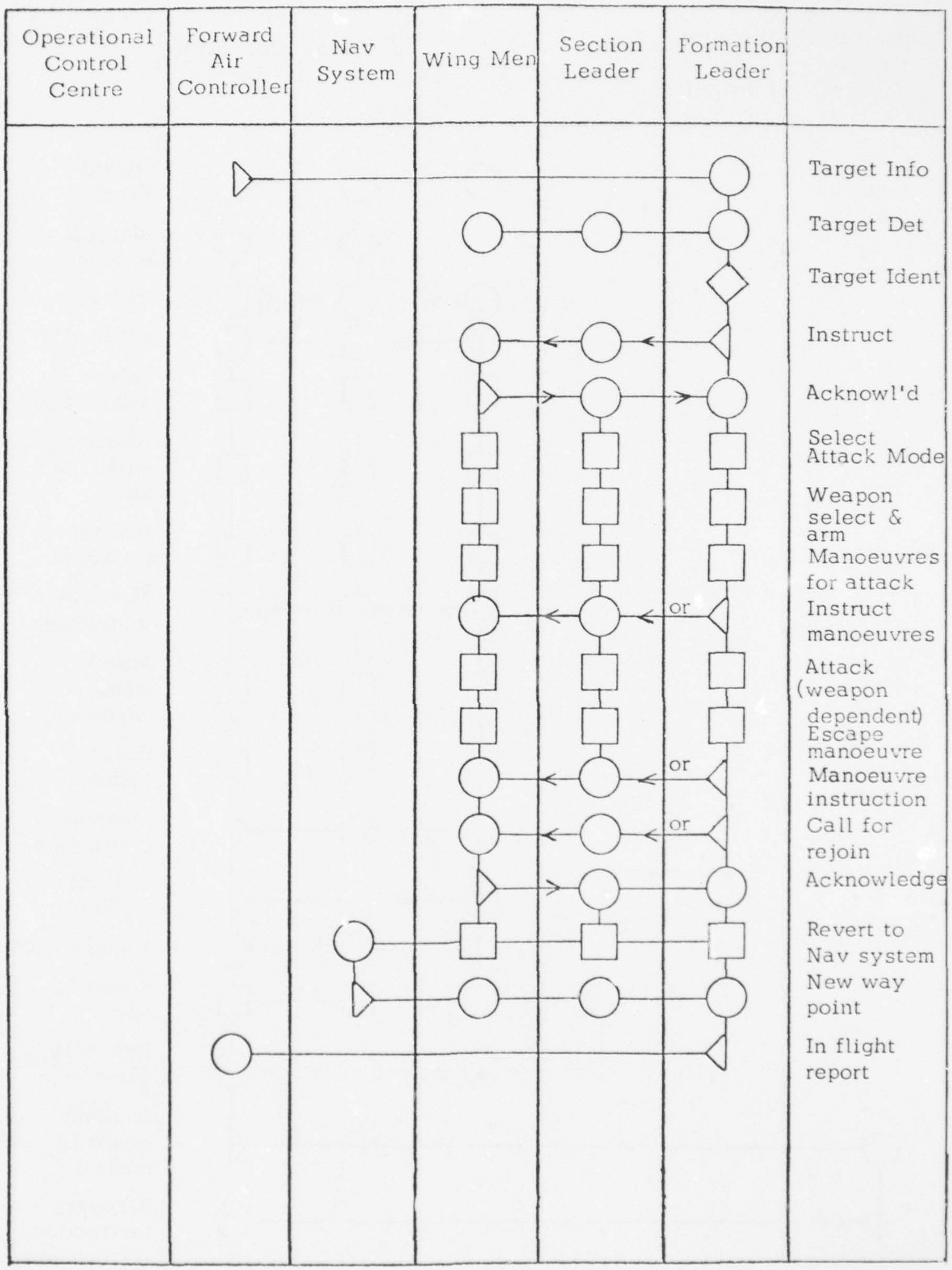


Fig.2.2 Forward air controller directed

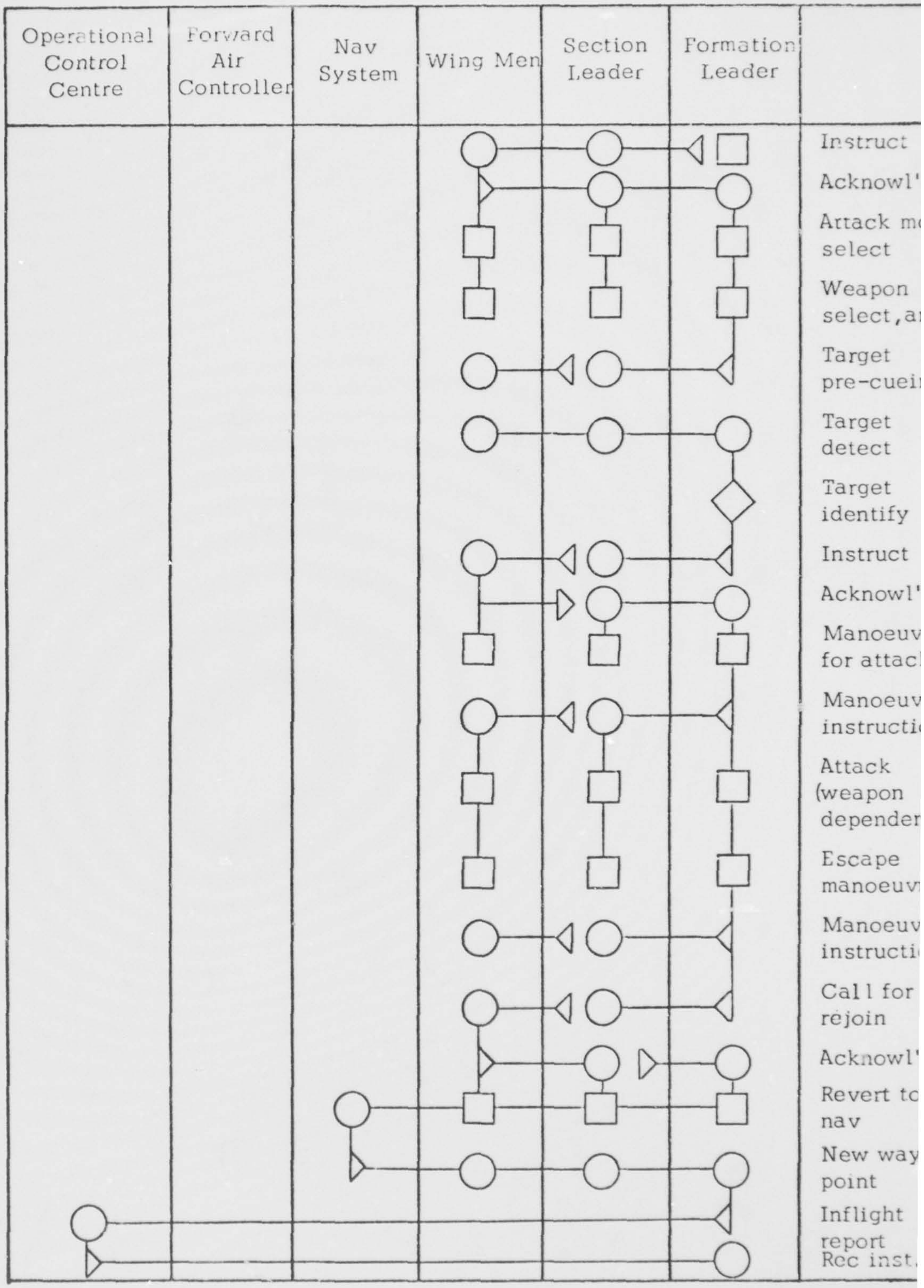


Fig.2.3 Pre-planned target

Section 3

CHAPTER 3

THE HELICOPTER

3.1 INTRODUCTION

The main theme of this chapter on helicopters is the optimisation of the balance between human capability and system automation with the object of providing the most effective operational system and the most cost effective designs of both helicopter and equipment.

As with fixed wing aircraft, the designer must ensure that the helicopter cabin environment will not adversely affect the crew's performance. He must provide the crew with the information that they require and have the ability to process. He must also arrange that the vehicle and its systems can be easily and effectively controlled.

In the past, these aspects have received relatively little attention in helicopters. Possibly, when the early helicopters were little more than curious flying vehicles with no specific role and the engineering and aerodynamic problems associated with them were great, the luxury of human factors input was very low on the list of priorities.

Today, helicopters perform a wide variety of specific tasks, ranging from low level "nap of the earth" type sorties of the smaller amy helicopters, to the tasks of anti-submarine warfare (ASW) or the transporting of heavy equipment by the larger helicopters. Now, unless human factors and system design expertise is applied to optimise the man/machine interface of the helicopter, the full potential of the system will not be realised. While much research still requires to be performed in this man/machine interface area, there are some areas where knowledge already exists and can be applied to the helicopter to improve the overall efficiency of the system.

A brief summary of these areas, and the essential differences between fixed and rotary wing aircraft are given below. Because helicopters are so markedly different from fixed wing aircraft in many respects, some of the helicopters' unique characteristics will be explained in detail.

3.2 COMPARISON BETWEEN HELICOPTERS AND FIXED WING AIRCRAFT

It is difficult to make direct comparisons between fixed and rotary wing aircraft. The helicopter's VTOL abilities result in it being used in different ways and for different purposes than fixed wing aircraft. However, some roles are performed by both types of aircraft, and two comparisons are listed overleaf. (See Table 3.1.)

Both the fixed wing Beaver and Scout helicopter have been used as British Army reconnaissance aircraft. Both types have similar weights, payloads and engine power, though the helicopter speed is lower and the engine power is greater. Similarly, the fixed wing Tracker and Sea King helicopter are used in the anti-submarine warfare (ASW) role. Weights, payloads and engine power are similar, though the fixed wing maximum speed is greater than that of the helicopter. In general, helicopters require approximately 1.5 SHP for every 10 lbs of all-up-weight, whereas propeller driven fixed wing aircraft require only about one SHP for each 10 lbs all-up-weight. Thus helicopters tend to have about 50% greater engine power than fixed wing aircraft for a given AUW. The ratio of payload to maximum AUW remains constant at around 40% for both types of aircraft.

Thus for a given aircraft weight, the payload, cruising speed and to some extent engine power both types of aircraft tend to be about the same. This is where similarities end and, from the human factors viewpoint, differences begin.

The helicopter has more human factors problems than the fixed wing aircraft. The mechanism for sustaining flight will now be examined to provide the reader with a better understanding of these problems.

Both helicopters and fixed wing aircraft depend upon the generation of lifting forces from airflow over aerofoil surfaces. The fixed wing aircraft generates lift mainly from its wings, as air flows over them in forward flight. The helicopter generates lift in a similar way, except that its wings or rotor blades are rotated through the air to create airflow over them.

TABLE 3.1

Typical Performance of Fixed and Rotary Wing Aircraft

	Max Speed	*Cruise*	*Weights*	*Engine Power*
British Army Reconnaissance Role				
Fixed wing	140 mph	135 mph	2850 – 5100 lbs	450 hp
Small helicopter	131 mph	122 mph	3080 – 5300 lbs	685 hp
ASW Role				
Fixed wing	280 mph	166 mph	18300–26200 lbs	3050 hp
Medium helicopter	159 mph	145 mph	12100–20500 lbs	3000 hp

In the fixed wing aircraft, when the pilot increases engine power to produce more thrust, speed and lift, the aircraft will continue to climb with little further adjustment being required from the pilot for some time. The pilot requires only a control column and rudder pedals to balance pitch, roll, and yaw of the fixed wing aircraft.

It is somewhat more complicated for the helicopter pilot when he wants to increase the rotor's lifting power to take off or climb. In general, because the rotor blades have considerable inertia it is not possible suddenly to increase their speed and lift by increasing engine power. Their speed is usually maintained over a narrow range between certain limits. Lift changes are accomplished by changing the incidence of the rotor blades. When rotor blade incidence is increased, more power has to be supplied so that the rotor speed is kept within its range by use of the throttle. To increase the blade incidence on all main rotor blades, the pilot is provided with a collective lever, which is held in his left hand. This lever also controls engine power, measured as manifold pressure on piston engine helicopters or as torque on gas turbine engine aircraft. On the older types of helicopter the throttle control, in the form of a twist grip, is attached to the end of the collective lever to control engine speed. This combination of controls can be considered as the up/down control for the helicopter.

The helicopter pilot also has a cyclic pitch stick in his right hand. This is used to change the pitch of the blades as they pass through a particular sector of the rotor disc in such a way that it tilts the rotor disc axis in a direction parallel to the stick. Thus the helicopter tends to move in the same direction as the movement of the cyclic stick.

If each control action could be made in isolation, then helicopter flying would be little more difficult than fixed wing flying. However, in the helicopter a change in position of any one control will have an appreciable cross coupling effect which will require adjustment of the other controls. If, for example, the pilot wishes to move forward from the hover position, he will push the cyclic stick gently forward. The helicopter will begin to move forward but will also start to sink. To prevent the sink, the collective lever must be raised to increase the collective pitch of the rotor blades and increase the lift. The throttle must then be used to maintain engine and rotor speed by increasing the torque to the rotor. The additional torque will yaw the fuselage in the opposite direction to the direction of rotation of the main rotor. This swing will have to be counteracted by the use of rudder pedals. All of these control actions will be performed almost simultaneously by a skilled helicopter pilot and are virtually unobservable by a layman.

Most control movements by skilled pilots are small but continuous in unstabilised helicopters for the majority of flight. This raises another difference between fixed wing aircraft and helicopters. The fixed wing aircraft is in general dynamically stable, which means that if it is disturbed in cruising flight, for example by a gust, after a few seconds it will return to steady flight without pilot action. Conversely, the basic helicopter is dynamically unstable. If it is disturbed by a gust during cruise, it will only return to the original conditions by action from the pilot or auto-stabilisation system if fitted. Thus continuous small adjustments must be made to the controls of the unstabilised helicopter just to maintain steady flight conditions.

The essential differences between the helicopter and the fixed wing aircraft, which are discussed briefly above, may help to explain why the helicopter has some human factors problems, in addition to those normally encountered in conventional aircraft.

3.3 THE HELICOPTER CABIN ENVIRONMENT AND ITS EFFECT UPON OVERALL SYSTEM PERFORMANCE

The basic differences between fixed and rotary wing aircraft referred to earlier in this Chapter, account also for the differences in noise and vibration environments within the cabins. The helicopter usually has greater installed power than a fixed wing aircraft of similar all-up-weight. The engine is coupled to the rotors via gearboxes and transmission systems which lead to still more noise and vibration. It develops lift and drag, somewhat asymmetrically, from its rotors and usually contains larger and a greater number of rotating components than an equivalent size of fixed wing aircraft. Any out-of-balance forces due to these rotating masses are transmitted as vibrations through the structure and finally through the brackets and seats to the helicopter equipment and crew. The vibrating structure and panels also act as additional radiators of noise.

3.3.1 Vibration

Usually the vibration spectrum of a helicopter is made up of low frequency, low amplitude background vibrations ranging from a few Hz to a few hundred Hz. Superimposed on this will be found a number of peaks of high amplitude vibration corresponding to the main rotor blade passage frequency, (5R if the rotor has 5 blades), the main rotor frequency R, multiples of 5R, e.g. 10R, 15R, etc., up to 40R perhaps, the tail rotor frequency T, its blade passage frequency and multiples of it, e.g. 6T, 12T etc. if it has 6 blades. Generally, the greatest peak is at 5R with still considerable energy peaks at 1R, 10R and 1T for a 5 bladed main rotor.

It is important to note that since the vibration peaks are generated by out-of-track or unbalanced rotor blades, asymmetric generated lift and drag forces, and blade vortex cutting, helicopter vibrations are not limited to the vertical axes but occur also in equal magnitude horizontally in lateral and longitudinal directions. In most fixed wing aircraft the predominant vibrations are vertical, and the horizontal vibrations are an order less in magnitude. Thus helicopter vibrations are usually greater in amplitude, direction and cause more human and equipment problems than those of fixed wing aircraft. The vibration problem contributes to reduced crew effectiveness, increased cost, due to the need for anti-vibration palliatives, increased maintenance, reduced component life and reduced helicopter utilisation. Reductions in vibration level therefore have immense long-term benefits.

There are short, mid and long term solutions to the helicopter vibration problem. In the short term, when a particular helicopter's vibration characteristics become unacceptable, it is usually the result of an out-of-track blade or worn component in the rotor or transmission system. Appropriate maintenance will reduce the vibration to an acceptable (though still high in comparison with fixed wing) level.

The mid term solution is to reduce the prominent vibration peaks by anti-vibration mountings of the equipment or man. Anti-vibration mounts are not always very effective in helicopters due to the large frequency range of the vibration peaks and the multi-axis nature of the vibration. For example, anti-vibration seats are often used to reduce the vibration to the vehicle crew. These seats, which consist of springs and dampers, are usually tuned to attenuate the vehicle's predominant vibration frequency in heave (vertical). One such seat was tested in a helicopter which had high levels of vibration at the 4R rotor blade passage frequency. Unfortunately, although this seat did remove most of this vibration in heave, it did little to attenauate the 4R horizontal vibrations. Furthermore, the seat natural frequency corresponded to the 1R frequency vertical vibrations. Thus the pilot was protected from some of the 4R vibration reaching him through the seat, but had to suffer far higher levels of 1R heave vibration which excited his body resonance in heave[2].

When a vibration problem becomes apparent, bifilar head vibration absorbers are sometimes incorporated into the main rotor head to reduce the level of vibration. Another method by which the existing vibration levels can be reduced is to make use of heavy components such as the helicopter battery. In some helicopters, the main battery is carried on a special mounting in the nose and a high resonance is induced in its mounts so that a vertical vibration node is forced in the cockpit area.

The long term answer to the helicopter vibration problem is to tackle it at or near to its source at the design stage. If a rotor and transmission system cannot be designed to have low vibration characteristics, then the fuselage and its human and avionics content must somehow be isolated from it. This can be engineered by attaching the fuselage to the rotor, gearbox and transmission assembly at positions which are the nodal points for the predominant vibration frequency. For example, the rotor-transmission system can be mounted on a beam whose nodal points are used as attachment points for the fuselage. In practice, the beam size is reduced by using a linkage of elastomeric bearings. A slight weight penalty is incurred but this is far outweighed by the benefits produced by the reduced vibration levels.

3.3.2 Noise

Noise is often a greater source of discomfort to the crew of the helicopter than vibration. Noise can reduce the crew's efficiency both indirectly by fatigue and directly by masking audio signals. It can also reduce the crew's hearing ability, both temporarily and permanently if they are exposed to high helicopter noise levels over a long period.

The noise reaching the ears of the helicopter crew is usually both greater and more complex than that reaching the pilot of a fixed wing aircraft of similar power. The helicopter, with its many rotating parts, generates aerodynamic noise from its rotors and engine, together with mechanical noise from the transmission and other systems. In addition, the crew will receive noise from the intercommunication system. The low frequency part of the acoustic spectrum is dominated by main rotor noise. This consists of rotational noise and broad band noise.[3]

Rotational noise has peaks of energy at specific frequencies and their harmonics which are related to main and tail rotor blade passage frequencies. Broad band or vortex noise usually has a band of random noise spread over a much wider frequency range. A typical main rotor would have its broad band noise energy concentrated in a band from about 200 to 800 Hz. For a two bladed rotor helicopter the rotational noise will be higher than the broad band noise. If the number of rotor blades is increased (other conditions remaining the same), the rotational noise will decrease by approximately 4 dB per blade and the broad band noise will assume more importance. Tip speed is also an important factor and as it increases so does the rotational noise level.

Another, essentially airborne, component of the noise spectrum comes from the engine. In the case of a piston engine the main source is the exhaust which produces harmonics of the engine firing frequency in the 200–1000 Hz range. With gas turbines, the inlet or compressor noise predominates. This is usually a high frequency whine of 10 kHz and above. The exhaust noise is usually masked by rotor noise and is therefore not a problem. A major source of cabin noise, which is largely though not entirely structure borne, is that of the transmission. This consists of gear meshing frequencies which contribute towards the broad band spectrum noise level. This transmission noise usually predominates at around 1000 Hz.

Human speech frequencies range from about 300 Hz to 3 kHz and this gear noise is particularly annoying because of its interference with communications. Another important source of noise which is often overlooked but which can adversely affect comfort and performance is that from the intercom system. This system will not only relay speech from the crew members, radios and audio warnings to the subject's ears, but it will also pick up cabin noise and electrically generated noise and feed it directly to the ears. Sometimes the additional speech and intercom noise to the existing cabin noise is sufficient to raise the overall noise level at the crew members' ears to damage risk level. For example, in a recent study of helicopter cabin noise, the noise at the crew's head position was found to be 108 dB or 100 dB (A). The noise at the ears was 99 dB or 90 dB (A) with the intercom off, due to the attenuation given by the protective helmet. With this intercom active, the equivalent continuous noise level will increase. If a crew member is exposed to levels greater than 90 dB (A) for 8 hours a day or 93 dB (A) for 4 hours, 96 dB (A) for 2 hours etc. throughout his working life, these levels will result not only in temporary hearing loss but in some degree of permanent hearing damage.

As with vibration, the noise problem is best tackled at the design stage, when it may be possible to change the primary noise sources. For example, noise may be reduced by increasing the number of rotor blades, introducing structural damping, or sound proofing, which must be incorporated in the original design. However, with existing helicopters it may be possible to alter the noise reaching the ears of the crew by modifying details of particular systems. For example, the crew might be provided with helmets which give good noise attenuation and thus reduce some of the noise which reaches the ears. Alternatively, the intercom system may be improved by changing the response of the microphones so that they are most sensitive over the speech frequency range, but less sensitive to other frequencies. This will prevent lower and higher frequencies from being picked up which mask the speech and other audio signals.

Similarly, an audio warning signal may be changed in frequency and re-shaped to be free of masking noise. Figure 3.1 shows how an audio signal in the 200–1.6 kHz frequency band is masked by gear meshing noise. By increasing the audio signal's frequency range to above 1.6 kHz the signal will no longer be masked by the noise. In addition, with this re-shaped audio signal the overall level of signal plus noise will be lower and this will reduce the danger of hearing damage.

3.3.3 Cockpit Vision and Display of Information

At present over 90% of all current helicopter flying is performed in daylight while in visual contact with the ground under VFR (Visual Flight Rules). Most of the information that the pilot needs to control the aircraft comes from visual cues outside the cockpit. Thus one of the most important requirements for a helicopter cockpit is that of good visual characteristics. Helicopter window areas should be, and in fact usually are, much larger than for fixed wing aircraft of similar size. Not only should these transparencies be large but they should be situated with the helicopter pilot's task requirements in mind. The helicopter often has to manoeuvre in restricted areas such as forest clearings, or heliports which are surrounded by trees, buildings and other obstructions. The pilot frequently needs to see downwards and rearwards and requires windows in the appropriate places. It is not always possible to incorporate these into the cockpits of big helicopters which have large freight cabins behind, but it can usually be accomplished with smaller helicopters if considered at the start of the helicopter's design process.

Some helicopters begin life with a more than adequate window area which is then reduced to an unsatisfactory level as additional equipment is fitted. Navigational aids and radios are among the worst offenders. Flight logs are sometimes fitted on top of the combing immediately in front of the pilot and these greatly degrade his forward view.

In the past, with low performance helicopters, window areas have been improved by moving some of the less frequently used controls and switches from the front panel up into the roof. With newer, high performance machines, this blanking off over the roof area is proving to be an embarrassment when performing steep turns and other similar manoeuvres.

To improve the view of the outside world from inside the cockpit, some manufacturers have resorted to the use of smaller instruments, about half of the diameter of the more common 2"–3" (50 mm–75 mm) diameter aircraft instruments. Although these result in smaller instrument panels, the miniature displays are often difficult to read accurately or quickly, especially when in the vibrating environment of the helicopter. They also tend to suffer from inadequate lighting for night flying purposes.

As has been mentioned above, although the majority of helicopter flying takes place under VFR, instrument flying is commonly practiced. However, true instrument flight, where the pilot gets no visual cues from outside, as for example when in cloud, requires great skill and effort, especially with an unstablised helicopter. Instrument flying problems also stem from the need to detect small deviations from the required flight path so that they can be corrected immediately and not allowed to build up into large errors. Instrument flight is not helped by the fact that often the principal displays found in helicopters were originally designed for fixed wing aircraft, though the crew information requirements in helicopters are almost certainly different. In-flight experiments have shown that pilot effort is greatly increased during instrument flight[1]. In one such experiment in an unstabilised helicopter, cyclic control movements were measured during both normal visual flight and instrument flight, so that a comparison could be made of pilot activity levels. During instrument flight in cruise, cyclic movements were found to increase by 65% over those during visual flight.

Thus, until recently the helicopter has been used primarily as a daylight operating vehicle. It has not been fully utilised throughout day and night because of inadequacies in control and visual presentation of information to the pilot. Clearly, great gains in operational effectiveness would be achieved if the helicopter pilot could be given a reliable automatic flight control system and easily assimilable flight information.

Several methods are currently available for presenting the outside world information that the pilot requires for helicopter night flying. These include image intensified night goggles, low light television and forward looking infra-red displays. Each device has its peculiar advantages and limitations. Although each type of night vision aid provides the ability to see in low light levels, the present devices also require a great deal of effort from the pilot. Their full potential will only be fully realised when the vision aid characteristics have been carefully matched to the requirements and abilities of the user. Current trends appear to be diverging from this philosophy. Considerable effort is being devoted to providing more and more information to the man. Few seem to have questioned what information is required by the helicopter pilot to perform his task and just how much he can process at any moment in time. For example, some helmet mounted displays provide a picture of the outside world upon which is superimposed a considerable quantity of information, normally displayed on the conventional head down cockpit instruments. Much of the latter is required only a few times per sortie, yet it remains cluttering up the display throughout the complete flight.

There is much to be gained in extending and almost doubling the helicopter's usefulness by enabling it to operate at night, but this will not be achieved, nor will it be cost effective, unless the pilot needs are matched by the information display interface.

3.3.4 Thermal Effects

No section about the helicopter cabin environment could be complete without some mention of the thermal effects upon crew efficiency. In the past the helicopter has had very little effort devoted to improving the cabin thermal environment. Some helicopters have possessed ventilation louvres for cooling. Others have flown with the doors removed in hot climates to reduce the cockpit greenhouse effect. A few have embodied hot air blowers to prevent window misting and to increase crew comfort for Arctic operations. (One such installation made so much noise and caused so much interference over the intercom that the helicopter crew always flew in the Arctic with the hot air blower off.) With the increased avionic fit expected in future ASW helicopters, there will be an additional need to remove the waste heat from this equipment and to maintain the avionics operators' efficiency by providing a reasonable cabin thermal environment. Consideration must be given to the means of providing a controlled thermal cabin environment at an early stage in the helicopters' design. There will be little chance of providing this at a reasonable cost retrospectively.

3.4 HELICOPTER AVIONICS

Avionic systems for military helicopters can be classified broadly into control, navigation/communication and weapon delivery aids. Further sub-division can be applied most usefully to the first and last of these viz. in the first case into manual and automatic flight control systems and weapon systems into target acquisition and weapon firing aids. The following paragraphs touch on each of these topics.

3.4.1 Control Systems

Firstly, it is of course a basic necessity that the helicopter be readily controllable. The particular ergonomic difficulties encountered in manually controlling a rotary-wing vehicle have been the subject of continuing research and stem from the basic ability of the vehicle to manoeuvre in the three lateral degrees of freedom. In the first instance alleviation of poor handling and stability characteristics was first sought in an avionic sense by the introduction of automatic pilot stabilising systems. The distinction between auto-pilots and autostabilisers is a fine one since with all current systems the pilot retains overall control of the vehicle's manoeuvring. The extent to which the system allows pilot intervention and imposition of his demands is particularly important in a helicopter which by its nature operates in close proximity to the ground and along profiles much less constrained by pre-flight planning than many of its fixed-wing counterparts. With current technology automatic systems are available throughout the spectrum bounded by simple rate-based stabilisers to full-time, full-authority manoeuvre demand systems. These latter enable remote control from various stations within the vehicle or even remote stations on the ground. For any future vehicle, the designer has to weigh a great many conflicting demands and viewpoints in deciding the level of automatic equipment he will employ. A first datum point will almost certainly be established by the vehicle's size, role and cost constraints. However, having established the general level of complexity, there still remain decisions that have significant impact to both the vehicles utility in its design role and even more on potential developments and attraction to customers other than the main sponsor. For example, there may be strong pressure from military users to design for single pilot operation when civil operators are seeking twin pilot machines. On the one hand, a highly reliable, failure tolerant system for single pilot operation may allow new designs to be used (with any attendant stability difficulties countered by the auto-control system) whilst a more cost-effective conventional design might be considered for civil application.

In the past the choice of control system was simplified to some extent because of the developing nature of technology with resulting reductions in size and weight. In addition clear improvements in performance were offered. A situation has now been reached in which gains of this nature are bought at an increasingly high price and the benefits become less readily demonstrated. Modern helicopters themselves are inherently easier to handle without resort to automatic control aids and the British Army is currently operating many unstabilised vehicles. It is in fact no coincidence that the major developments in automatic control techniques have occurred in naval helicopters and in particular for ASW vehicles. This naval role is well suited to automatic control, the dunking of sonar systems being a well defined operation that can be readily automated. The benefits in terms of safe and predictable operation in all weathers are also clearly obvious. Army requirements on the contrary are for highly versatile vehicles commanded directly by the pilot who of necessity is an active participant in the manoeuvring and direction of the vehicle. Since it has always been difficult to measure human work load unequivocally and normal processes of adaptation and training can seemingly cope with a wide spread of handling characteristics it is not surprising that Army operators will examine avionic aids critically. The lesson would appear to be that it is dangerous to assume that an automatic control system is essential and cost effective if the human operator has to be fully engaged in manoeuvring the vehicle no matter what are the handling criteria.

A corollary to the above in some measure is the use of avionics in relation to flight instrument displays. On a number of occasions during the past thirty years attempts have been made to devise special instruments for helicopter applications. Perhaps one of the more interesting lines pursued was that of the Flight Director principle. Much time and effort was devoted to these systems without any obvious lasting progress and currently they are little considered other than for limited civil applications. Flight directors found favour in fixed wing aircraft because of the frequent need to operate under Instrument Flight Conditions. Very little of this type of operation – along well defined flight paths is encountered in military helicopter operations. Unless either the pilot or a crewman has visual contact with the terrain many helicopter sorties are abortive. Thus to slavishly incorporate flight directors into the cockpit is a mistake especially when ground support facilities such as homing beacons and approach control aids are lacking. To be most effective in enabling helicopters to operate in poor visibility, means must be sought to maintain the normal visual link with the terrain. Hence the current interest in imaging systems based on LLTV and FLIR technology.

Since, initially, it will be most difficult to retain or substitute for this usual link in the fullest sense, recourse will be made to automatic vehicle stabilisation to remove the difficulties of extracting short term motion cues from the synthetic image or picture. Thus whereas, with normal wide fields of view the piloting task is quite manageable, current limitations on synthetic images demand complementary stabilising aids. It is in these types of limited visibility flying conditions that a proper balance between avionic aids, cost, weight and size is going to be difficult to achieve.

3.4.2 Navigation/Communications

Now the second major area of interest, namely, navigation will be considered. It has long been appreciated that a major difficulty of piloting helicopters is a knowledge of position and the direction to navigate. Attempts to solve this problem have resulted in expensive IN systems and moving map displays quite incommensurate with the nature and characteristics to current helicopters. Limitations in cockpit space, the difficulties of presenting large scale maps and the high order of navigational accuracy required pose major difficulties in solving the problem. Ideally an autonomous system is demanded to retain the flexibility and independent nature of helicopter operations. Even accepting a dependence on ground aids, currently available techniques do not adequately cater for very low altitude operations normally encountered in military flying. It would seem that promising developments will occur in the field of imaging sensors that can be interpreted against conventional maps, albeit with assistance from basic dead-reckoning computers to maintain a rough running check on position.

The importance of good communications for both military and civil helicopters cannot be over-stressed. Whilst radio communication equipment continues to improve in terms of size and weight with the advent of new electronic technologies, the basic problems of poor propagation paths to low flying helicopters remain. Coupled with these is the need to operate with a wide variety of ground stations, mobile military units etc., demanding high flexibility in the communications systems. Problems of aerial siting on helicopters are great, they are not eased by the introduction of composite or glass-fibre fuselage panels even on the larger vehicles. No less important is the question of good communications between crew within the helicopter; this is exacerbated by the poor noise environment mentioned earlier.

The whole navigation/communication system design demands attention to a number of each factors, many of them conflicting, and a greater understanding of the impact of each factor on operational efficiency is demanded before the best solutions can be arrived at.

3.4.3 Weapon Aiming Systems

Finally the topics of weapon aiming systems and surveillance aids should be considered. As yet this subject as applied to the helicopter has received relatively little attention, but is becoming increasingly important. Emphasis will initially be centred on means of acquiring and identifying targets as the capability of helicopters to deliver significant weapon loads is increased. The need to have a front cockpit crewman dedicated to surveillance and weapons control increases the need to ensure that the helicopter can be flown by a single pilot in all weathers. Thus it will be even more essential to design an effective fit of control and navigation aids.

In summary the procurement of cost-effective avionics can only be achieved by a careful and objective assessment of the role of the helicopter and its crew. Whilst this has occurred in a natural fashion in the past, it will be more difficult in the future as equipment designs reach their development plateaus. It will be necessary to review concepts of pilot and crew workload to ensure they are still valid in the light of new vehicle and engine designs and establish a thorough understanding of the problems of integrating systems, displays, and controls throughout the aircraft.

3.5 CREW ACTIVITY ANALYSIS

Methods by which the pilot or crew capability and avionic system design may be optimised as far as crew activity is concerned, are common to both fixed and rotary wing aircraft. They fall into the two categories of:

(i) Study of crew activity patterns in existing aircraft systems.

(ii) Examination of role expected for future aircraft and corresponding synthesis of crew activity patterns to highlight and resolve problem areas.

3.5.1 Existing Helicopter Examples

Some problem areas can often be determined by studying crew activity patterns during normal flight operations. For example, this has been done in both helicopters and fixed-wing aircraft[2] by flying on typical sorties and filming pilot activity and tape-recording the intercom for later analysis. Multiple activity charts of pilot head and hand movements have been plotted and times for each activity have been calculated. By recording the activity of different pilots in the same aircraft, and of the same pilots in different aircraft, while performing a variety of tasks, a set of activity patterns have gradually been built up. Studies of this nature have revealed that activity patterns of well trained pilots tend to be a function of task and, to a much lesser extent, of the individual pilot, type of helicopter or equipment fit. Activity analysis has shown, in this case, that with existing small to medium size helicopters, that if a pilot has to fly at very low level due to tactical reasons, then he might spend up to a third of his time looking inside the cockpit, when he really needs to spend 100% of his time looking outside for ground hazards. This has highlighted the problems of very low level flight and indicated that improved flight control systems, navigational aids and radio aids are required, together with engine, fuel and transmission systems having greater reliability than are available at present.

3.5.2 Activity Synthesis of Future Helicopter Operations

Before pilot or crew activity patterns can be synthesised for a future helicopter project, the role of the proposed aircraft must first be examined. When this role has been established, together with the aims, objectives and likely constraints upon the helicopter's operation, the significant crew activities needed for this role can be defined. These crew activities can then be broken down still further and quantified more precisely. Time-line analysis can be used on the synthesised tasks and interactions between crew and equipment and between individual crew members can be studied with the purpose of determining where the crew members are overloaded. When these peaks in activity have been established, re-scheduling of activity patterns or additional computer assistance, can be investigated as means of removing the overloads.

This type of technique has been applied already to helicopter and other projects, by human factors groups within the aircraft industry. It has proved to be a useful method of indicating where man/machine system shortcomings might arise, how they might be overcome and generally gives the system's designer a clearer understanding of the project: (Detailed examples of helicopter flow diagram routines are not shown in this chapter, since they would follow similar lines to the fixed wing examples).

3.6 CONCLUSIONS

Although this chapter has indicated that there are some major differences between fixed-wing aircraft and helicopters, there is one problem area common to both types of aircraft. That is man's ability to cope with the final system. Man is usually the weakest link in the man/machine system. It is true that he can be trained to cope with systems which are difficult to operate, but there is an obvious limit to the amount that he can be trained to do. At the start of any helicopter design study, the man's abilities and limitations should be taken into consideration.

From an examination of present helicopters, it would appear that helicopter vibration and noise problems receive attention only after the helicopter has been built and is flying. Instead, the helicopter and systems designers should initially determine the role expected of the helicopter and design it, its avionic systems, its intercom, etc. to be compatible with each other. As experience has shown, it is futile to expect an intercom system designed for a relatively noise and vibration free pressurized fixed wing aircraft to work equally well in the environment of an assault helicopter which flies at low level with its doors open.

Careful analysis of the expected operational role of the helicopter should be made and any predicted high peaks in the crew's activity should be examined in detail. Ways to overcome these work load peaks, should be studied, making use of man's unique abilities where possible and automating areas where man's capability is limited.

Assuming that the crew's activity peaks can be smoothed out and the man/machine interface optimised, there is still the problem of the helicopter vibration, noise and thermal environment. Unless this is taken into account in the early stages of the design process, the full potential of the crew and helicopter are unlikely to be realised.

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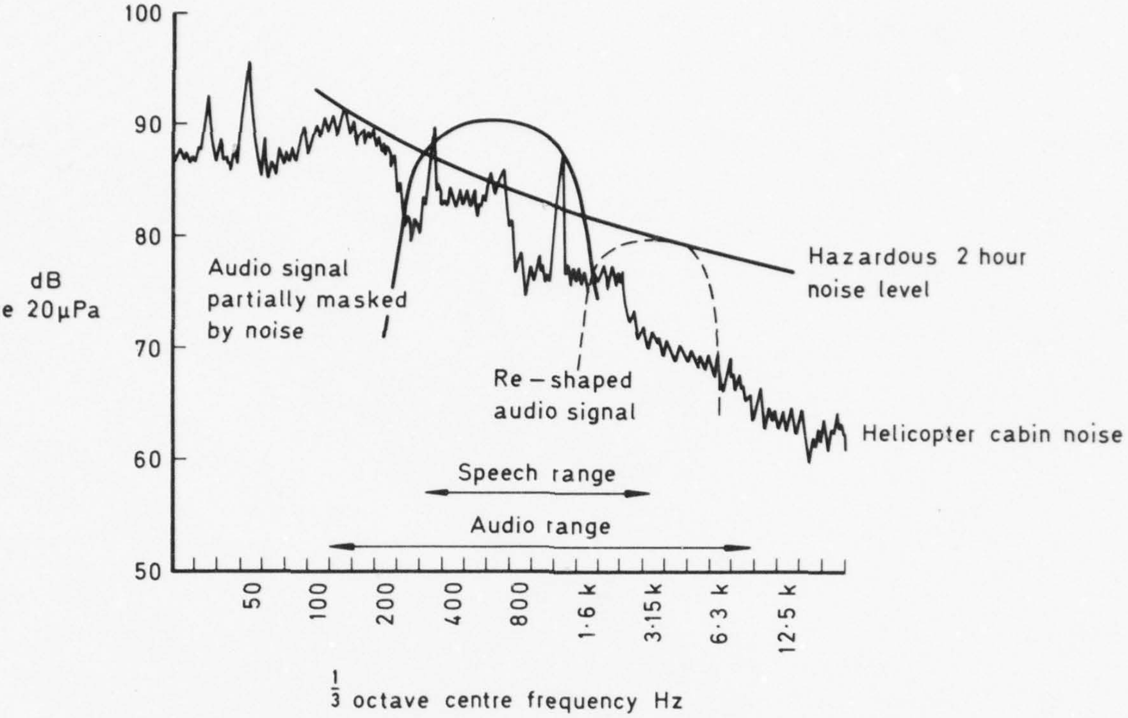

Fig.3.1 Typical helicopter cabin and audio signal noise at operator's ears

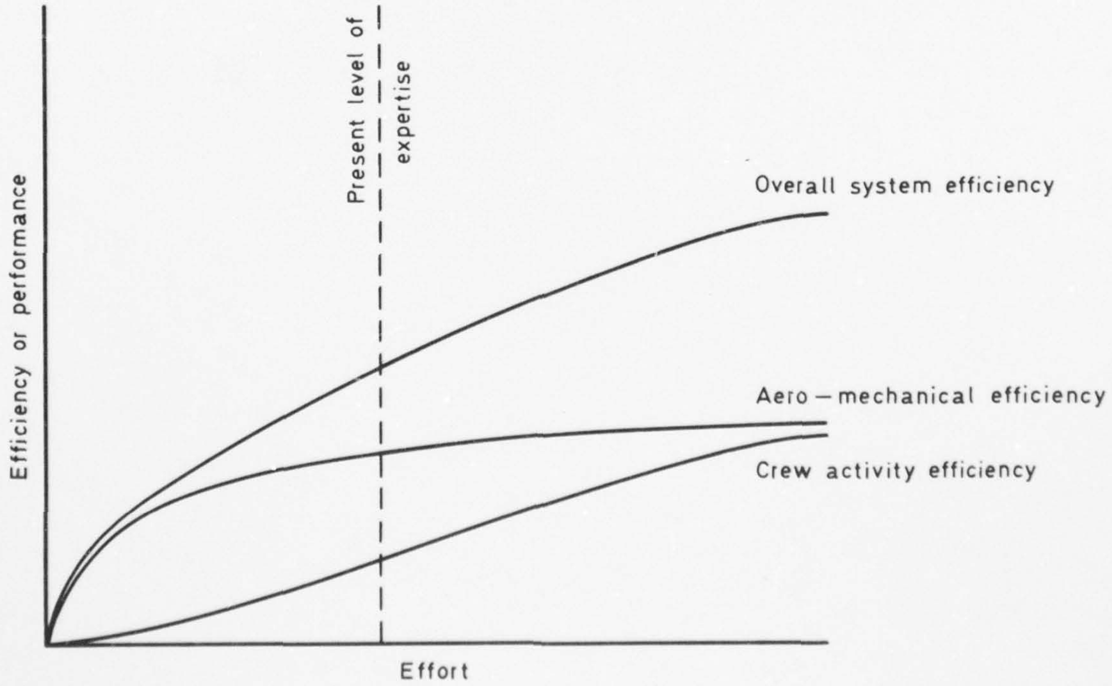

Fig.3.2 Conceptual relationship between engineering and crew efficiencies which combine to form the overall man/machine system efficiency

SECTION 4

CONCLUSIONS AND RECOMMENDATIONS

Section 4

CONCLUSIONS AND RECOMMENDATIONS

1. This last Section presents a summary of the highlights and conclusions of the several studies by members of the Working Group and their advisers and consultants. The recommendations have been simplified to provide a series of objectives and the appropriate research still needed in addition to current work. The cost of such research has not been suggested but it should be not more than much of that which is usual for continued programmes upon some of the more sophisticated avionic systems. The goal of the research recommended here is twofold namely, an increase in total operational efficiency and a reduction in aircraft capital and maintenance costs.

2. Professor Bosman has described his proposals for a methodology which should permit the system designer to apply at least some scientific order to attempts to achieve a better man machine interface. He states that current simulator technology offers the means of realistic evaluation of typical problems. Feedback from pilot experience has been the usual manner in which ergonomic solutions can be evaluated. This process should continue. Such methods will not help computer designed systems however. Research should be encouraged therefore in the non-technical man-machine interface aspects to obtain harder and usable data for application to the interface matrix. In the opinion of the editor, this will require a continuous exchange of information and requirements between the system and human factors engineers. Some progress has been made so far in this direction but it is very limited and will require a better exchange of available experimental results.

3. Dr Hartman has provided a wide range of physiological information which should guide systems designers who should be encouraged to have the abilities and limitations described in mind at all times. It would be advantageous if some of the material available in the further references was also digested. The simulator is a valuable tool for combined system and human factors research, and it is in this respect that many of the future human factor problems can be identified for further research.

4. Dr Reynolds chapter upon training outlined the activity allocation concept and in agreement with Professor Bosman's approach she has emphasised the use of task analysis to review the man to equipment ratio for the successful completion of a task to establish behaviour objectives in training. Comparative studies of individual and machine capability are suggested but this should not be the only programme.

A major factor in life cycle costs concerns personnel, and trade-off studies must consider this aspect carefully. More data is needed, particularly in the assessment of points of overload. Improved instrumentation should make it easier to obtain measures of physical, physiological and psychological limits. The recommendation for research into more objective performance measures of training effectiveness has been stressed by Dr Reynolds. More intensive pursuit of such research is needed. A further step in the right direction can be achieved by the early identification of those skills which are essential to successful performance. Consequently selection and training procedures should be improved.

5. The conclusions and recommendations relevant to the three aircraft roles considered in this report are easier to define. This is not unusual and is evidence for the cases presented by the three basic human factors authors. The air superiority fighter aircraft requires specific research into problems which are identical in some instances with the needs of all air combat aircraft. An aspect of particular concern is the sighting of hostile aircraft and it is recommended that more effort is applied to the design of long range television and infrared sensors to enhance the pilot's visual range by several orders of magnitude.

Dr Reising recommends further examination of the use of cueing boxes or circles on the display format. This should help the location of sensor detected targets beyond visual range. This technique would employ the integration of say radar and visual sensors. A serious problem is the identification of the type of threat after initial detection. The threat may be seen in various attitudes creating visual illusions and distortions to the pilot. Research is needed to improve pilot ability to recognise threats or targets in unusual attitudes. It is suggested that, with the aid of a tachistoscope and a slide projector, illustrations of threats or targets in various combinations of attitudes and ranges when shown to pilots would allow a measure of viewing time, ranges, aircraft types and attitudes to be examined. Such experiments may give a more realistic measure of identification range than hitherto.

Further research is suggested by Dr Reising upon the improvement of threat avoidance capability. The elimination of pilot confusion caused by the combination of auditory and visual threat displays in a high threat environment is vital.

Current threat priority algorithms, used to eliminate clutter, could be improved by further research. Type, status and range of threat need some optimizing function which will weight these parameters and determine a 'threat score'. The research should consider the form of the function, such as linear or quadratic and the values of weights for various parameters.

To improve target destruction capability and increase friendly aircraft survival the manoeuverability of aircraft, and best use of available energy are important items of current research which should continue. The display of energy state is in its infancy and a great deal more research is needed in this field. Parameters requiring particular attention include methods of displaying Ps, maximum corner velocity, maximum sustained turn rate, and an indication to the pilot as to how to obtain various energy parameters.

6. The particular problems requiring further work to improve the air to ground attack role concerns the identification of targets from the large amount of clutter expected. Head out of the cockpit operation will be essential for the single seat aircraft and this will require improved methods of presenting data in digested form. Automatic filtering of data is the only way in which a low level attack can be effective since, unless terrain following or avoidance systems are employed, the effort required to avoid ground collision will seriously detract from the efficiency of target identification and selection. It is considered that human factors will set the limit upon further effective use of EO sensors.

Wide angle of vision for both pilot, or second crew member if available, will become essential as improved missiles are developed. It is to be expected that head mounted sighting and display systems will become even more important. Control problems are however a most serious matter and such systems as direct voice control (DVI) offer a means of alleviating pilot workload in combat, and increased effort should be applied to it.

7. Helicopter and systems designers should initially determine the role expected of the helicopter and then design the total system to be compatible with each other for that role. The helicopter intercommunication system for instance has a very different environment in which to work as compared with a fixed wing aircraft system. Careful analysis should identify any high peaks in helicopter crew activity. Ways to overcome these work load peaks require study, to make the best use of man's unique abilities where possible, automating areas where his capability is limited.

Assuming that the helicopter crew activity peaks can be smoothed out and the man/machine interface optimised, early stages of the design process must take account of the vibration, noise and thermal environment early in the design process.

REPORT DOCUMENTATION PAGE

1. Recipient's Reference	2. Originator's Reference	3. Further Reference	4. Security Classification of Document
	AGARD-AR-118	ISBN 92-835-1292-8	UNCLASSIFIED

5. Originator
Advisory Group for Aerospace Research and Development
North Atlantic Treaty Organization
7 rue Ancelle, 92200 Neuilly sur Seine, France

6. Title
OPTIMISATION OF PILOT CAPABILITY AND
AVIONIC SYSTEM DESIGN

7. Presented at

8. Author(s)/Editor(s)	9. Date
Edited by F.S.Stringer*	November 1978

10. Author's/Editor's Address	11. Pages
* Procurement Executive Ministry of Defence The Adelphi London WC2N 6BB, UK	104

12. Distribution Statement
This document is distributed in accordance with AGARD policies and regulations, which are outlined on the Outside Back Covers of all AGARD publications.

13. Keywords/Descriptors

Avionics
Airborne computers
Microprocessors
Pilots (personnel)
Pilot training
Work measurement
Fighter aircraft
Design criteria

14. Abstract

Recent advances in avionic systems technology offer facilities to combat aircraft designers to transform completely the potential of engines and airframes into more powerful total weapons systems. To date there has been no serious attempt to equate the problems created by increasing complexity and cost of systems with the costs and benefits offered by aircrew. The ability of aircrew to achieve benefit from systems without an unacceptable attendant level of cockpit workload, requires study.

These contributions by authors with backgrounds related to diverse disciplines, sets the scene and offers some guidelines for future research. The book is an introduction to the subject to all who are concerned with the design, procurement or operation of military aircraft.

The Report was sponsored by the Avionics Panel of AGARD.

AD-A062 409 ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT--ETC F/G 5/8
OPTIMISATION OF PILOT CAPABILITY AND AVIONIC SYSTEM DESIGN.(U)
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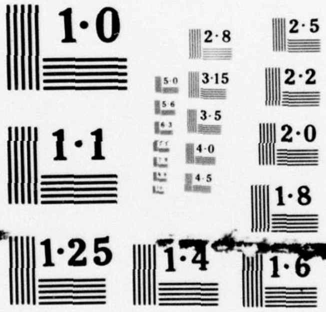
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AGARD Advisory Report No.118
Advisory Group for Aerospace Research and Development, NATO
OPTIMISATION OF PILOT CAPABILITY AND AVIONIC SYSTEM DESIGN
Edited by F.S.Stringer
Published November 1978
104 pages

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Avionics
Airborne computers
Microprocessors
Pilots (personnel)
Pilot training
Work measurement
Fighter aircraft
Design criteria

AGARD Advisory Report No.118
Advisory Group for Aerospace Research and Development, NATO
OPTIMISATION OF PILOT CAPABILITY AND AVIONIC SYSTEM DESIGN
Edited by F.S.Stringer
Published November 1978
104 pages

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These contributions by authors with backgrounds related to diverse disciplines, sets the scene and offers some guidelines for future research. The book is an introduction to the subject to all who are concerned with the design, procurement or operation of military aircraft.

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