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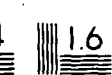




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The Impact of New Guidance and Control Systems on Military Aircraft Cockpit Design

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THE IMPACT OF NEW GUIDANCE AND CONTROL SYSTEMS
ON MILITARY AIRCRAFT COCKPIT DESIGN

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NORTH ATLANTIC TREATY ORGANIZATION
ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT
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Papers presented at the Guidance and Control Panel Symposium held at the
Theodor-Heuss-Kaserne, Stuttgart Bad-Cannstatt, Germany on 5-8 May 1981.

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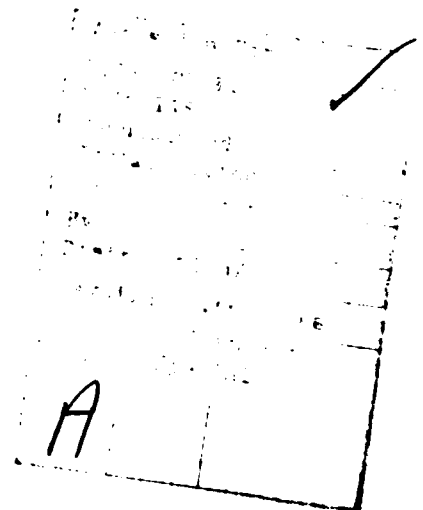
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THEME

In recent years, the role of the pilot particularly in single crew aircraft, has changed dramatically. The advances in flight control weapon aiming systems, navigation and communication systems coupled with ECM and many other capabilities has presented a real challenge to the Aircraft System Designer and in particular to the design of a cockpit layout with controls and displays that maximize the overall aircraft capability while keeping the pilot's workload within bounds by the use of more automation of system management. The air-to-air and air-to-ground attack missions are becoming very demanding and the range of munitions from free fall bombs and guns to agile guided weapons presents system integration problems which also reflect into cockpit design.



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* Paper not available at time of printing.

† Published in CP-312 (Supplement) – Classified.

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* Paper not available at time of printing.

† Published in CP-312 (Supplement) - Classified.

TECHNICAL EVALUATION REPORT

by

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1. INTRODUCTION

The 32nd GCP Symposium was held at Theodor-Heuss-Kaserne, Stuttgart, Germany, 5-8 May 1981. The program Chairman for this meeting was the Panel Chairman, Mr G.C.Howell, of the RAE Farnborough, UK. The full text of the papers is published in the Conference Proceedings CP-312 and CP-312(Supp.) (Classified).

2. THEME AND OBJECTIVES

In recent years, the role of the pilot, particularly in single crew aircraft, has changed dramatically. The advances in flight control, weapon aiming systems, navigation and communication systems coupled with ECM and many other capabilities have presented a real challenge to the Aircraft System Designer and in particular to the design of a cockpit layout with controls and displays that maximize the overall aircraft capability while keeping the pilot's workload within bounds. The air-to-air and air-to-ground attack missions are becoming very demanding and the range of munitions from free fall bombs and guns to agile guided weapons presents system integration problems which also reflect into cockpit design.

Recently, big strides have been made in some cockpit designs for fighter aircraft as well as helicopters (F-16, F-18, ADAS UH-60A). This indicates a reversal - long overdue - of the trend towards proliferation of cockpit equipment items to be watched or operated by the crews. It was timely, therefore, for the Guidance and Control Panel to hold a symposium in 1981 on "The impact of new guidance and control systems on military aircraft cockpit design" in order to help rationalize and hasten this trend reversal NATO-wide.

The objectives of the symposium may thus be stated as follows:

- (i) Bringing into focus the *present knowledge* in cockpit design as it exists in the different NATO nations, by exchange of views and experience amongst the experts in order to stimulate, or correct where appropriate, their work.
- (ii) Considering the progress that might be achieved through better *integration* of the task oriented ("dedicated") cockpit equipment for the multitude of tasks that have become possible, and therefore appear desirable to be performed, within the operational capability of a single aircraft.
- (iii) Reviewing *new technologies* for cockpit use that have become available, or appear feasible in the near future, and assessing their possible contribution to lowering the crew workload, lowering the maintenance effort, increasing cost effectiveness and increasing mission success.

To achieve these objectives the symposium was organized in six sessions

- I OVERVIEW REQUIREMENTS/TECHNOLOGY
- II DISPLAYS
- III CONTROLS/DISPLAYS SYSTEM INTEGRATION
- IV AUTOMATED SYSTEMS/MAN INTERFACE
- V COCKPIT SYSTEMS EVALUATION
- VI FINAL DISCUSSION.

3. TECHNICAL EVALUATION

3.1 Session Review and Highlights

For the *keynote address* very wisely a well experienced member of the military user community was chosen to introduce early in the proceedings a damping effect on undue "new technology" enthusiasm and a warning against misusing a fighter cockpit to manifest how much can be packed into it in the way of displays, switches controls, selecting devices and warning systems. The speaker introduced the very valid concept of the "Raw Guy", the less experienced and less well conditioned pilot for whom the cockpit has to be designed as opposed to a finger artist and mnemonist. This "Raw Guy" notion was well born in mind by most subsequent speakers and discussion contributors. Two further points of importance to the aircraft users and with consequences for the cockpit design were well made, viz. "mission abort due to minor battle damage cannot be tolerated", and "fingers cannot be used to operate densely arrayed keyboards in battering low level flight".

3.2 Session I – Overview

The first paper of Session I gave a broad and richly illustrated "overview" of all the considerations that have to go into the design of a multifunction cockpit. It fitted well the theme of the Session. Of necessity, the wide scope of this paper prevented deeper penetration of individual aspects. As most of the important items are well treated in subsequent Sessions, and unfortunately no text of the presentation has become available to this reviewer, a more detailed appreciation cannot be given here, but readers are referred to the full text in these CP.

The second paper (2) somewhat missed the theme of the conference in that it stressed the ergonomic aspect of the pilot's seating arrangement without really discussing the implications of such new ergonomic findings for the G & C interest of the meeting. Unfortunately, for time reasons, no discussion followed that might have filled this gap.

The third paper (3) very competently addressed the helicopter aspects of the Session. It brings some interesting examples illustrating the introduction of digital technology, in particular of multifunction displays (MFD), into helicopter cockpits, including ADAS (Army Digital Avionics System), which is treated in more detail in paper 10, see below. This paper went well with the theme of the Session and is well worth reading again.

The next paper (4) began with describing a basic methodology for future, "post 1990 time period" fighter cockpit design. The main text, however, causes one to place this design less far ahead: only two very brief references, viz. that to a "voice command/concept" and to "visually activated switches" seem to go beyond well known present day technology as, for instance, it is demonstrated in paper 26 (F/A18). An interesting point is the assumed use of a multiplex data bus system, MIL-STD-1553 B, duplex for avionics – and stores management and triplex for the flight control system which is also being used in ADAS, see paper 10. The paper did not provoke any discussion.

The last paper (5) of this Session again missed the concise conference theme by describing the pilot's ejection seat arrangement – very much inclined to the rear – and its effect on general cockpit geometry. No discussion followed.

This first Session suffered more than subsequent ones from a near total lack of discussions, mostly due to the presentations exceeding the allocated time. With more foreknowledge, i.e. availability of preprints, better use of the time allocated to the Session might have been achieved, by giving more priority to papers 1 and 3 at the expense of others.

3.3 Session II – Displays

The first paper (6) discussed the development – in small steps to avoid unacceptable "quantum jumps" – of an electronic display arrangement for transport aircraft. It uses, in its final form, 6 colour cathode ray tubes as the display medium for a crew of two, and it is claimed that the feasibility of operating a large transport aircraft (Airbus) with such two-man crew was thus established. A standardisation of colour coding was attempted by using green for fixed scales, magenta for selection inputs, white for present indication and red for warnings or limits. It is stated that colour tubes are now available that give three times the resolution of ordinary TV tubes. These rugged shadow-mask tubes give low reflectivity to ambient light and therefore good contrast of display. If necessary, this may be further enhanced by externally mounted filters. Status: Flight testing in a BAe 1-11 of the MOD, UK in progress.

The following paper (7) concentrated on the mixing of synthetic monochrome images, derived from FLIR or LLLTV and monopulse Radar imaging, in a wide angle HUD (30° opening), for use as night vision device. Computer generated symbology for guidance and control information is superimposed on the composite landscape image. Status so far: Laboratory tests only.

Paper 8 gives a thorough and most valuable treatise of all the facts to be considered in the development and use of colour displays. In addition to CRT-technology it covers the characteristics and abnormalities of human colour perception, e.g. its variation with the viewing angle. Some of the more interesting conclusions of the paper are "Addition of colour provides a visually pleasant experience; pilot's performance, however, does not significantly improve statistically". "Colour is not helpful when brightness contrast is great; it is beneficial at very small brightness contrast between target

and surround". The appropriate use of colour coding can lead to substantial performance improvements; the inappropriate use of colour coding can increase the workload and cause confusion". It was particularly regrettable that, also for this paper, there was no time for immediate discussion.

The last paper of the Session (9) concentrated on the technology and use of head-up displays, stressing the need for increased width of the field of view, up to 30° or 35°. This is partly connected with the use of off-boresight weapons, for instance air to air missiles with $\pm 60^\circ$ lock-on angle. Small increases would, in this case, be meaningless. The cure would be helmet mounted displays as a complement to HUDs.

The papers of this Session were more balanced in their relevancy. They covered the field well, particularly when the additional information from unavoidable overlap from other Sessions (e.g. Papers 10, 22) is taken into account. Unfortunately again, no contribution could be derived from discussions after the presentations because of their near complete absence.

3.4 Session III – System Integration

The first paper (10) links up with paper 3 on Army Helicopter cockpit design (much overlap!). It describes the process of control and display integration in three steps, ending up with ADAS. The reduction in cockpit complexity can best be judged by the comparison of the number of items required for different control and display functions in an illustration that was shown during the presentation and is repeated here (Fig. 1). Status: First flight evaluation in a UH 60-A in about one year's time.

This paper provoked some discussion on pilot's acceptance. UK pilots are still somewhat sceptical as to the reduction of workload; as a negative example the time necessary to switch radio frequencies was mentioned. It was quoted that an evaluation test with 12 pilots did not, initially, convince them of an improvement. This changed to full acceptance in night flying tests, where it was found that one serious complaint with the old cockpit system had completely disappeared, viz. the tendency of the aircraft to rise inadvertently after an input command was initiated.

The next paper (11), a very thorough and comprehensive study, begins with a philosophy on the writing of requirements for the standardisation of control and display units (CDU) for multi-aircraft application. Not only the usual issues form, fit and function but also the interface to the flight crew has to be considered, and this can vary considerably from a spacious cabin of transport aircraft to a tight fighter cockpit. Also growth capability has to be considered. In the application of the resulting requirements to a practical standardised design many useful experiences are gained and reported in the paper, covering also the issue of information processing, the pros and cons of distributed microprocessors, the tie-in with MIL-STD-1553 multiplex bus system etc.

A lively discussion followed the presentation, bringing out further interesting points such as: Key operation in the presence of vibration (helicopters) requiring some further human factors research on push distance and push force; red and amber in colour displays should not be continuously present but should be brought on when actual warning is due (non-familiarisation!); software for all applications should be part of every CDU rather than procuring individual aircraft software. The keynote speaker again made a strong plea for the standardization of keyboards and asked the GCP to initiate action.

The following paper (12) described one particular sample of practical development experience, the change from analogue to digital RADAR imaging for the Tornado in terrain following missions and the improvement achieved. There was some discussion on the different requirements of the three user nations. The relevance to the Session theme of "integration" was not evident.

Also the next paper (13) on a miniaturized throttle box, a piece of ingenious mechanical design, had little to do with the Session theme, albeit it describes a stepper motor drive for the throttle which lends itself to integration with digital fly-by-wire control systems. Status: prototype not yet tested.

3.5 Session IV – Automatics/Man Interface

Beginning with the argument that even multifunction controls do not always reduce workload, paper 14 sets out to open up an alternative or additional communication channel between man and machine through voice control. (The paper is based on the findings of an NADC conference two weeks earlier). A further argument in support of this move is based on MFC's undiminished reliance "on the already saturated visual/manual information channels". On this point one may have reservations as to the implied conclusion that an additional channel, viz. voice interaction, can unburden another existing channel of excessive load; the bottleneck still remains in the human brain itself with its limited independent access channel capacity, no matter whether visual or aural. Nevertheless, an aural channel has distinct advantages, when sharing attention with a visual-input/manual-output channel. If sufficiently infrequently used in operation it catches attention more easily than the visual channel through its "arousing" effect utilized in voice warning systems. It also interferes less with manual aircraft stabilization and trim than additional switch or control manipulations by hand would do.

The discussion brought out probable limitations that might persist even after some further development of a voice interactive system, e.g. in high stress situations and under high-g-condition. Noise poses a minor problem, e.g. breathing noise when using an oxygen mask. Status: breadboard system for tests in an FD-16 aircraft started in Jan.81, more general availability expected in two years' time.

As a well fitting complement to the first paper of the Session, paper 15 reported on a comprehensive French research program. One of the conclusions is that a voice control system always needs "personalization", i.e. adjustment to the individual user's speech characteristics, to obtain good speech recognition performance. This personalization is achieved by means of personal sonagrams, taken on tape (personal cassette) beforehand. The recognition of a word or command by comparison with this sonagram needs 100 to 400 milliseconds time. Tests gave 99% success in speech recognition in the absence of noise disturbance, and 98% when using an oxygen mask. When breathing is hampered (high g) it is difficult to find the beginning and the end of a spoken word. Mask development appears necessary.

The discussion stressed the danger of mixups between similar sounding words. Standardization of a vocabulary of about 100 carefully selected words and selected syntax are good tools against this. The recognition time delay must be further investigated to assess its effect on airborne tasks. 400 milliseconds appear unacceptable but 200 to 250 might be tolerated. A military operator's discussion remark stressed that he would not wish to look at the recognition success in terms of 98% success but rather on the — to him and others — unacceptable remaining error rate of 2%.

Paper 16 returned to the less futuristic objects discussed at the conference and stressed the human factor side in looking critically at different existing or proposed manual multifunction input devices. A plea made earlier (in the discussions to paper 11) was vigorously supported, viz. to resolve the dilemma of alphanumeric keyboards by standardizing within NATO the "telephone-norm" as against the general "computer and business machine standard". He pointed out — and lucidly illustrated by examples — the other dilemma of either having a multitude of dedicated switches clustering the cockpit surfaces in the conventional way or using multifunction input systems and accepting sometimes markedly increased operation sequence times.

In a discussion remark the author, an expert in anthropotechnical aspects, clearly favours the cockpit arrangement of the F-18-Hornet (paper 26) as the best present day solution for fighter aircraft.

Papers 17 and 18 described actual experience in specific fighter system developments.

The discussions stressed the point that too many switch or pressbutton operations, when changing targets during attack, either take too long to perform for the time available or increase crew workload unbearably. (Paper 26 describes one way of overcoming this with the HOTAS concept). A plea was made for touch-sensing displays because under combat stress they would permit larger errors in correct finger pointing than pressbuttons.

Paper 19 again stressed the advantages of digital data techniques particularly in their application to "utility systems", i.e. mechanical systems such as powerplant management, secondary power, hydraulics, fuel management etc.). Distributed microprocessors with central management (INCOMS) are proposed.

In the discussion the question of colour coding was raised. Red and amber should be reserved for warning functions, green for "Go" status. The point was made that red print has poor readability and might better be replaced by a red rim around black print. (In another discussion it was proposed to use amber colouring for warning, progressively changing into red when alerting is required. Permanent red symbology or lettering would cause diminishing attention.)

Paper 20 endeavoured to establish a philosophy and methodology for more efficient information management in avionic systems. It did not provoke any discussion, probably because its approach was somewhat uncongenial to practical engineers.

3.6 Session V — System Evaluation

The first paper (21) described statistical measurements of helicopter pilot's and navigator's eye movements in monocular sight (one eye blanked off with cardboard mask). The effect of a stepwise reduction of the field of view on the scanning of the outside view and the instruments and the relation between the two is described. No discussion followed.

Paper 22 described results and conclusions of extensive systematic flight investigations of an optical system for helicopter low level operation at night or in poor visibility. A helmet mounted sight and display (HMS/D) is used in conjunction with a slaved infrared camera (Mini-FLIR). This (or any other low light level camera) is mounted on a gimballed platform underneath the helicopter and provides outside visual information for terrestrial navigation, which, after mixing with symbols for instrument derived information, is fed to the HMS/D.

The discussion on the difference in results between this sophisticated system and the less expensive use of night goggles brought out the important advantage that the HMS/D can be used with a variety of image producing sensors or their combination. Nevertheless, the alternative use of goggles during certain phases of flight is not precluded (Fig.5 of the paper). With goggles, normal cockpit instrumentation can be read by looking underneath the lower goggle rim.

In the paper the suggestion is made to let one member of the crew use the HMD/D for target acquisition whilst a second member uses goggles and HDD for safe navigation in low ceiling conditions. In a reply it was stated that the observed servo lag of the camera motion caused no complaints in the slow changes of attitude during navigation tasks, that for tracking, however, some improvement may be desirable. Further experience is needed in more difficult conditions at night.

A quite different approach to feeding extra information into the HMS was offered in the subsequent paper (23). A matrix of light-emitting diodes is used as an image source. It is at present intended to transmit energy-maneuvrability information in combat situations. Assessment is in progress at RAE, Farnborough. So far pilot's reaction is cautious. The helmet is considered to be too unwieldy in operational aircraft and HUD is preferred. Thus doubts as to the final outcome exist.

Paper 24 described an apparently successful tool for the assessment of pilot workload, an elusive quantity but indispensable as a yardstick when judging the relative merits of alternative or modified display formats and control handling qualities. The investigation uses the "secondary task performance" method by presenting an item recognition task in the form of letter combinations in the centre viewing field of a HUD, which can easily be done in actual flight with software modifications to the HUD picture generation system. The flying task, standard instrument approach, had to be chosen such that it was not noticeably affected by the secondary task. The results were surprisingly consistent and informative.

The discussion revealed a disparity between the quantitative measurements of second task error rates and the Cooper Harper ratings. The opinion was offered that the rating scale was perhaps not so good as originally anticipated.

Paper 25 described in great detail the TAACE program, an effort to evolve, through systematic mockup and flight simulation investigations a functionable and non-too-sophisticated or expensive tanker cockpit modification for a new crew combination without a navigator. To avoid excessive workload on the remaining crew some cleaning up of the dashboard, the introduction of two electronic multifunction HSIs and an electronic navigation management system (CRT plus keyboard) were tried and found to produce a promising solution. Status: "Final determination of feasibility of operating the tanker without a navigator has yet to be made".

The final paper (26), certainly a highlight of the symposium, demonstrated a very high standard of integration of MFDs, HUD and weapon management in the single place F-18 cockpit. The lively discussion that followed quite generally cast serious doubts on the need for multicolour displays in the near future (the F-18 does well without). In answering a question of battle damage it was demonstrated that serious consequences could, in fact, be reduced by a strategy of careful distribution of redundant items. The question of safe operation of pressbuttons under vibration was taken care of by arranging the multifunction keyboard in the F-18 to stick out by 4" so that the operating hand can be steadied on its sidewall. All instruments can, in a cockpit as narrow as that of the F-18, be kept within a 19° viewangle of the pilot.

3.7 Session VI – Final Discussion

Are Cockpit Technology Advances Meeting Operational Requirements for Military Aircraft?

The moderator briefly reviewed what had been said during the week and drew his conclusions from this. Then, in lieu of a "round table", he asked a few selected experts for their views before opening the general discussion.

In referring to the keynote speaker he reported the operators case as follows:

needed is

- more military effectiveness from each aircraft,
- more availability, also in hostile weather,
- less vulnerability, in increasingly hostile environments,
- increased integrity, no increase in peace time training loss rate
- improved maintainability, as part of keeping cost of ownership low.

Solutions indicated during the meeting are (i) miniaturised equipment using less cockpit area, (ii) multifunction displays and controls to permit a time multiplex use of more information, different weapons or flying modes, (iii) automation for pilot relief "in the hopeful knowledge that the things he is not looking at are being taken care of", and finally, the hope for future use of new information transmission means like colour displays and voice interaction

Compromises will have to be made in each cockpit design, to fit the operational task, the inexperienced "Raw Guy" (training costs!), the economic limits etc. Care has to be taken not to use sophisticated solutions in the wrong area.

Addressing the operators directly, the moderator showed sympathy with their reluctance to accept keyboards, MFDs and automation which they do not yet feel they can trust, but they should realise that the "Raw Guys" of tomorrow have grown up with calculators and playing Star Wars, and might be quite willing to accept sophisticated technology. Furthermore, he thinks that more automation in the cockpit may well reduce the amount of information the pilot needs access to.

In addressing the designers in the field, he pointed out the experience that they used to meet integrity and availability demands by duplication and triplication of equipments which inevitably increases cost of ownership at every level. Is this trend irreversible, he asked. If so, it might lead to more and more cost per aircraft, fewer and fewer aircraft in the front line inventory, and hence pressure to make each one do more, thus increasing the workload on the pilot and new attempts to introduce additional expensive equipment to alleviate this, a truly vicious circle.

In the discussion the military speakers explained their hesitancy with respect to automation with the experience that too many promises had been made in the past which have only partly come true. Too often something had been "just round the corner" but the corner never was reached. They are concerned that training requirements would go up with new and additional capabilities, and training is very expensive. A point of previous discussions was brought up again, viz. a plea for a cautious approach to new systems, and for the avoidance of "quantum jumps".

The cockpit designers side, in turn, complained about the lack of design directives from the military, and indeed, also this conference would have benefited from better participation of military staff and in particular of defence analysts.

The question came up whether mechanical standby instruments, which appeared in the most odd corners in some of the illustrations of advanced cockpits, could be omitted altogether. Opinions varied from: "These instruments will be with us for a long time yet, they are a cheap insurance, new pilots who graduate from simpler training aircraft are used to them", to the other extreme of "They are unnecessary when their original purpose is better served with the inherent integrity of several multifunction displays that permit mutual image exchange, and which are combined with redundant sensors and data buses". If, however, mechanical or electromechanical instruments remain indispensable, they also should be developed further to better match their use in flight to that of their electronic counterparts. They may well be kept out of the way in normal flight and mechanically swung in front of the pilot, when need arises in an emergency.

One contributor from the military procurement side wondered why contradictory conclusions as to the best arrangements of military cockpits persist, and often can be supported with apparently valid evidence derived from inhouse evaluations and tests (checked against selfmade criteria). He believes that the solution of this dilemma is a question of establishing common criteria and guide lines first, that eventually should be made mandatory. As examples he suggests.

For every single piece of information the cockpit builder offers on a display, he himself should carry the burden of proof that it is absolutely needed.

Information on functions that can be automated should be omitted.

The pilot is the link in the loop with the most uncertainties, with variations in mental and physiological performance and little "reconfiguration capability". Therefore, in case of trade-off-doubt, the pilot is to be given priority.

Other noteworthy remarks in the open discussion may briefly be listed:

Alphanumerical indications ("digitals") for fuel gauges and similar applications should be avoided when analogue or qualitative indications are easier to perceive and will do the job.

A most desirable development would be a man/computer interface that rejects human erroneous inputs.

It is regrettable that, as distinct from the car industry, in the military aircraft business customers do not come back to press for MK II or MK III simplifications.

A conciliatory note now and then came into the discussion, when the technical people, the researchers and designers, although occasionally blamed for overmuch enthusiasm for technological novelties and sophistication, repeatedly endorsed the pleas of "Keep it simple" and "Have the courage to omit things that are not proved to be vital".

4. SUMMARY AND RECOMMENDATION

From a Guidance and Control aspect the cockpit is the vital interface between the human operator and the highly complex cockpit systems which, on the one hand, provide him with information and, on the other hand, require attention and enable manipulation. Thus the conference had to consider all three facets of the cockpit design problem. It can be said that this was on the whole well achieved although the symposium sessions were organized according to a different scheme. Thus the important definitions of the human operators capabilities and limitations are given only implicitly in the keynote paper, in the discussions, and some special aspects in several papers (e.g. human vision in paper 8).

The conference theme naturally put emphasis on the more recent technology developments. A serious problem had, paradoxically, arisen from such a development of the technical means for the provision of information as well as for the manipulation and activation. These means have become progressively "avionic" with consequent chances of

miniaturisation, vastly increased capabilities and flexibility. This has permitted and encouraged a proliferation of human interface channels that ran wild. It was shown in the conference (see attached Fig.2) that some fighter aircraft accumulated up to 320 switches and more than 70 displays around one crew member. This must cause concern (see keynote) because of the implications for training needs, for maintenance and for many other aspects. Fortunately, a drastic change of this proliferation trend was indicated and in fact its feasibility demonstrated by examples of the latest cockpit developments for fighter aircraft (F-18-Hornet, paper 26) and helicopters (ADAS, paper 10; see also Fig.1 and 3) with much reduced numbers of interface channels.

Many papers of the conference addressed individual aspects of the total interface, showing modern ways of rationalising the systems and their operation, and thus achieve impressive relief in cockpit clutter and pilot's workload.

The most obvious tools are, on the information side, the multifunction CRT displays, which permit the suppression from the displays information in which the pilot is not currently interested; he need no longer filter this unwanted information out mentally. They are also able to integrate in a most logical way information from different sources such as e.g. route and weather data. The transfer of information to the human brain can be enhanced by a great choice of symbol shape, prominence and, if desired, colour. This latter facility of using colour, now available, is contested, however, for fighter cockpits. Even when it is restricted to sparse colour coding more harm can be done by inadequate design than good, it is stated (paper 8).

For the "reverse flow through the interface", i.e. for the selection and control activities of the pilot, great benefits have been derived from a careful application of interconnected switching, so that the pilot's actions are moved to a higher hierarchical level with fewer operations necessary. And of course automatic control is applied wherever and whenever the task to be performed is fully predictable, e.g. feed-back regulation of disturbances and stabilisation of flight path, again permitting the pilot to operate on a less busy higher hierarchical level, where his intelligence rather than routine skill is required. Furthermore, very good examples were shown of logically integrated management blocks, e.g. for CNI tasks, fuel and engine management, weapons, or the "utilities". Keyboards are introduced, combined with mode or address selectors to operate through a single multifunction input system what hitherto had been done by means of hundreds of dedicated switches. Caution, however, is indicated because the keyboard operation sequences can take longer than operating a dedicated switch (paper 16). There is obviously room for further research and development.

On the whole, the conference in its total, i.e. papers and discussions together, covered its three objectives, quoted at the beginning, well. Unresolved and open for future research and Panel interest are the questions:

When is colour necessary in displays; what can and should be standardised in colour coding, which colour for which parameter?

Which standard key arrangement should be made mandatory for military aircraft cockpits (telephone or calculator norm?)

Can HOTAS (Hands On Throttle And Stick)-operation of displays, function selection and controls be standardized? Can it be combined well with the use of keyboards, which fails in high-g-flight and extreme bumpiness?

Will voice interaction become necessary? Can existing combat stress effects, elocution effects, noise interference be mastered?

4.1 Presentational and Administrative Remarks

With the exception of a few points the meeting arrangements were well received. (Here the reviewer has to rely on his own impressions from scanty conversations because only three(!) questionnaires were returned.)

Complaints were concerned to a great extent with hardy annuals, such as: absence or late arrival of preprints, illegibility of visual aids because of small print or colouration of slides (an abhorrent but apparently ineradicable habit) made worse by apparent difficulty of focussing, overstepping presentation times at the expense of discussions, habit of reading lengthy extracts from written papers (killing attention), and excessive use of unexplained abbreviations and new colloquialisms with little consideration for the majority of non-experts in the hall.

AGARD should not relent in bringing its advisory notes for authors to the notice of contributors and remind them again at the beginning of the conference; Panel members should give good example.

Although the conference arrangements were excellently planned for a NATO Confidential meeting, it is questionable whether the place of venue, a "Kaserne", with its incongenial atmosphere, an oversize symposium hall that had to be kept in complete darkness in order to permit insufficiently bright projections to be read, and the total absence of nearby facilities for informal discussions and contacts, was conducive to effective interchange of views (objective (i)). The really excellent non-technical excursions arranged with impressive personal engagement by the local host Panel member, however, made good for much of the sombre atmosphere of the barracks. Also the excellent refreshments provided punctually during conference breaks helped in this.

One critical comment on the conduct of some sessions stated that more flexibility in handling time allocation, setting the technical scene and linking papers to the theme of the session, occasionally even filling gaps by the chairmen would have been desirable.

An obvious shortcoming was the lack of discussions in the initial sessions. Chairmen of these early sessions obviously have a more difficult task because people have not warmed up yet, and they must be prepared for this extra burden.

4.2 Recommendations

- (i) The complex integration process of cockpit systems for information display, CNI facilities, function selection, and control will, with increasing use of distributed microprocessors, continue to change cockpit design at a swift pace. Thus an early follow-on symposium on this theme should be envisaged.
- (ii) In further AGARD activities the treatment of weapon system architecture, that was spared out in this conference, should find a place, perhaps in conjunction with (i).
- (iii) In symposia of this nature a real effort should be made to strengthen the participation of military staff and defence system analysts.
- (iv) Early availability of preprints must be achieved to enable session chairmen, moderator and reviewer to do their job effectively, for the benefit of all participants and those who wish to profit from the final report.
- (v) Session chairmen should be permitted and encouraged to set priorities with respect to time allocation in order to better achieve the symposium objectives.

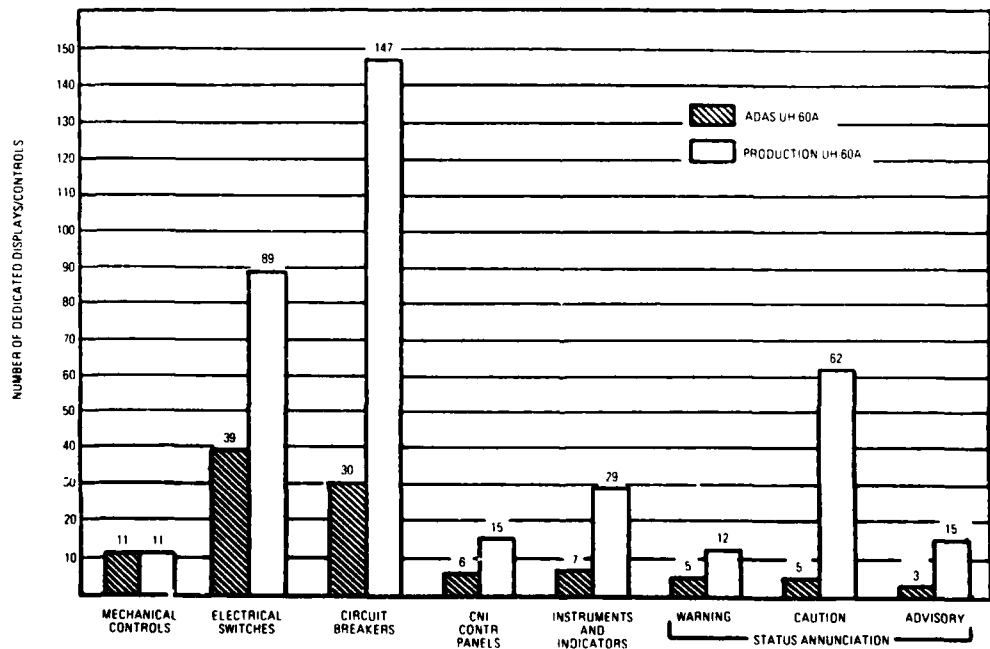


Fig.1 Cockpit control/display differences for production and ADAS UH-60A configurations
(Source: Slide from Dasaro's oral presentation)

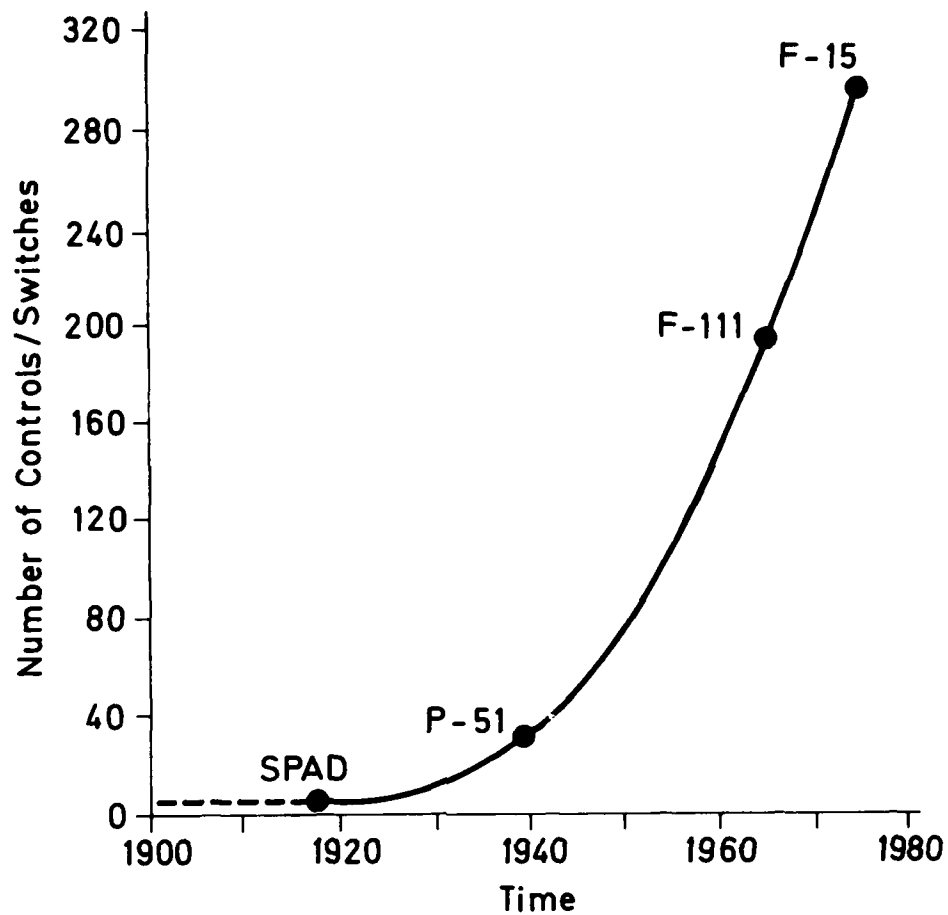


Fig.2 Number of controls/switches per crew member for 4 aircraft: SPAD, P-51, F-111, F-15
(Source: Ostgaard, Paper 1)

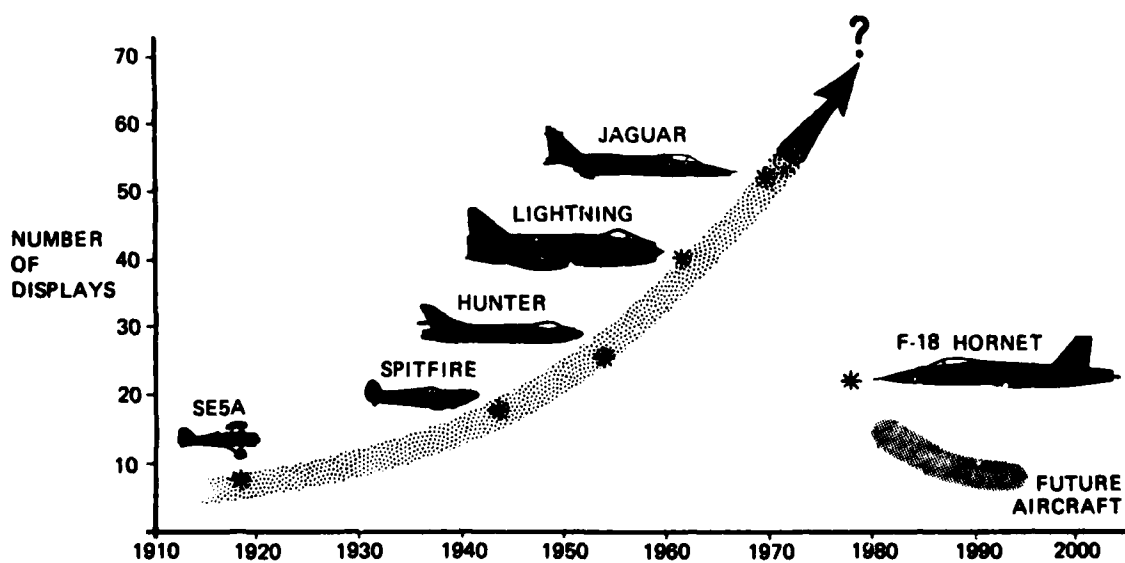


Fig.3 Growth of cockpit displays
(Source: AGARDograph 255, p 12-22)

The Impact of New Guidance and Control
Systems on Military Aircraft Cockpit Design

by

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It is a much appreciated honour to be with you all here today. Presumably you expect your key-note speaker to fulfil certain conditions and functions, perhaps to speak to you, august scientific body that you are, in scientific terminology; certainly to possess engineering qualifications; perhaps to dazzle you with an impressive knowledge of the subject of the symposium, and to theorize with lucid prescience. If that is so then you will probably find me somewhat unusual. For you see before you a simple pilot, without any scientific or engineering qualification, with an ability to speak only a simple form of the English language, and with a recently acquired superficial knowledge of the intricacies of new guidance and control systems.

However, I suspect that perhaps my lack of erudition may have influenced those who chose me as your speaker today. Certainly my hope is that a quarter of a century spent in the cockpits of Vampires Meteors Canberras Hunters Gnats Buccaneers and Hawks among others, and much of that time spent in the analysis and training of young men in the arts of basic and advanced flying, high-speed low-level navigation, and weapons delivery, will enable me to kick-off your discussions and deliberations this week in a useful way with a healthy dose of realism culled from experience of past and present cockpits, and from a quite extensive review of some possibilities for the future. Add to that my opinion about the difficulties facing a pilot in future operations and the problem of training him and you have the outline of my address to you today.

It is my aim to review philosophically the qualities needed in tomorrow's cockpits, and hopefully to convince you who will design and build the aircraft of the future of the absolute need to bring realism and practical experience into every stage of the development of the working environment of those pilots who will be pointing their little pink bodies at the ground in 1996 as I first did in 1956.

It might be worth a mention that this is the very first AGARD Meeting I have attended, so that the scene is quite new to me. On the other hand some of you may never have experienced my scene - flight at high-speed and low-level. Perhaps therefore it would help us all to get on frequency for the week, and put me more at ease if we took a look at some recent film of two modern European aircraft operating at low-level which I hope will bring the smell of kerosene to your nostrils, and will also enable me afterwards to paint a picture of the ordeal that could face a young, relatively new pilot tackling his first operational mission over hostile terrain.

I should like to call this relatively new pilot RAWGUY because I believe we could usefully adopt him as our best working model for the most difficult of new cockpit designs. We shall be returning later on to Rawguy, and in your later deliberations this week, I hope that he may figure prominently.

In viewing this film clip which lasts about 6 mins would you please try to imagine yourself in the cockpit, either as the pilot, if that is appropriate, or as a navigator. Whether you are an experienced aviator or not does not matter.

That film to my mind, impressive though it may be, still leaves a rather cosy, unrealistic impression of what it is really like inside the cockpit at 480 or 540 Kts, and particularly of what it may well be like in a hostile environment in Europe, as Rawguy flies along at 100 ft trying desperately to update the Nav/Attack system, make his weapons selections, interpret and react to the threat warning and stay in formation all at the same time. The film also cannot portray the heat, the noise, the discomfort in turbulence, the sweat, the excitement and the grip of fear, all of which will have a detrimental physiological effect on our young man, pitched in to battle during the early stages of his first operational tour on a low-level strike/attack squadron in Europe. But you may question why we should use this man, this role and this theatre as the particular model for future cockpit design. Well, it seems to me that one of the most difficult roles in the future, as at present, will be medium to long range counter-air operations here in Central Europe, whether by day, or even, by night.

Let me just draw your attention to an interesting comparison published recently in Aviation Week. Figure 1 shows the extensive array of defences pilots would have to face in a visual day medium to high-level attack. At low-level the formidable mobile ZSU 23-4 (radar laid) would have to be added. Figure 2 is Aviation Week's assessment of the effective defence facing a night low-level attacker, and I believe it is reasonably accurate. A night attack also neutralises enemy day-fighters, perhaps several thousand of them, and is likely to be a much-preferred option once the problems of achieving successful night attack are resolved.

The critically small numbers of highly-complex and expensive aircraft available for employment in this counter-air role will mean that losses will become even less acceptable than they are now. It will be essential for the weakest member of the attacking formation, unit or stream, to get his weapon on to the target and get his aircraft back to a safe haven to carry on the fight. That weakest member is Rawguy. In past wars he either survived the first few sorties to become a useful veteran or he was lost. In the most recent wars Rawguys have been lost together with their machines, and air forces have reluctantly recognised that some losses were inevitable. However, in future we shall no longer be able to afford to lose Rawguy, because we shall need his airframe and weapons system to survive. Good training can do a lot to assist his survival and I believe we shall have to be very firm in all our NATO air forces to resist so-called "economies" in fuel and flying training time simply to maintain present standards of operational training.

But regardless of quality of training which is not rightly the topic of this meeting, other factors must be recognised. Rawguy will not have been in combat before. Remember, he will be excited, fearful and clumsy. So he will not be flying the aircraft like a test-pilot, or yet like an experienced pilot, for his sum of airborne experience may be considerably less than 1000 hours, and he will probably fly less than 20 hours a month regularly. In addition, his allocation of live weapons for practice, and total weapons training time, will probably have been ludicrously inadequate. He will have his work cut out (particularly in a single-seat aircraft) simply to maintain formation, look-out and fly the aircraft. His cockpit workload has got to be reduced to the minimum and his potential to err in switch selection or system management must, as far as possible, be eradicated. In your deliberations about future designs, please consider Rawguy. The test-pilots and the old hands with whom you will be dealing must be made to find out what problems Rawguy encounters in his training and in his present day operational flying and then interpret those problems to you the designer. Too often in the past, cockpits have been designed on the basis of wrong advice, perhaps from very sound pilots, and in some cases, advice has been ignored for the sake of expediency, to result in disaster and expensive subsequent modification.

I believe these same principles can and should be applied to support helicopters or air defence aircraft or anything else, but that it is the low-level counter air mission that presents the worst case, where cockpit design deficiencies could overwhelm Rawguy and cause his demise, and the loss of his essential weapons system.

In my research for this address today, people have spoken to me with great enthusiasm, and quite rightly so, of "quantum jumps" in new cockpit design, of "watersheds", of "leaps-forward". I remember the same words being used to introduce the Hunter, the Lightning and the Jaguar. Yet what radical problems we had with all, once in service. There is extremely strong circumstantial evidence to suggest that at least one NATO air force has lost several pilots and new aircraft in recent years because so-called "quantum jumps" and changes in cockpit systems had been inadequately thought out and led to intolerable increases in workload at critical times, in some cases even for highly experienced pilots. Insidious HUD failures; need for too much head-down time; differences between HUD and HDD displays, have all been identified as causes of very near accidents and are believed to have caused some of the fatalities. New designs should ensure that Rawguy can cope with any change (for it is unlikely to have been incorporated in his early training) and that it will not catch him out.

The integrity of new cockpit systems must be made to match that of control systems. There should be complete similarity between HUD and HDD in instrument flying modes, so that in a head-down situation the pilot can quickly scan a familiar picture, and also so that rapid cross reference between HUD and HDD is possible without a significant change of scan pattern.

"Quantum jumps" fill me, admittedly a conservative, long-in-the-tooth trainer, with some trepidation, and my experience makes me suggest that they should be made as slowly and as carefully as possible, checking at every stage with present day front-line crews to ensure that the practical applications and possible drawbacks are not overlooked. As a typical example, take analogue instrument presentations which in some new designs already under discussion, may disappear except in certain flight modes. The analogue instrument is often a most valuable trend indicator, or even a comforter. What would happen to a pilot who noted from his digital CRT page that JPT (or TGT or TGIT or whatever) was abnormal? He would wish to monitor the figure continually, and he would be happier and safer with an analogue indicator to include in his scan, without the complication of calling it up on a multi-mode display from time to time, possibly thereby disrupting his attention to other important matters and in turn, the progress of the mission.

Can future designs be subject to computer check programmes that forecast the results in the cockpit of the failure of any system or individual item of equipment?

Touch-sensitive system displays sound wonderful but only for stable, transport aircraft. It is hard enough for a battered and vibrating low-level pilot in full NBC kit to hit the right switch with the proper amount of pressure, let alone finger the correct point on a CRT display.

It is very exciting to see the prospects that future technology holds out in terms of continuous system monitoring and automatic warning and remedial action, CRT displayed mission modes, direct voice input equipment et al, but can we please try to ensure that we do not prevent new aircraft from being used or flown manually, ensure that we permit the pilot "in extremis" to fly and to deliver his weapon by hand and eye, like in the past. I know that I shall probably be regarded as a heretic in saying this, but there is going to be a hell of a lot of scrap metal hurtling around the FEBA and around the skies near our enemy's airfields and in many other places, so airframes are quite likely to be well-riddled, and there will not be enough time to repair them. Should we not have the ability to fly the aircraft gear-down without hydraulics, to get around without INAS (that's training largely); to project or release a weapon using a simple device? Is quadruple redundancy in control systems really enough to overcome possible losses? Mission abort as a result of minor battle damage will be even less acceptable than ever. Also damaged aircraft may finish up at bases far removed from their own maintenance facilities, and in the desperate situations that could face us in future all-out conflict, we shall need to get those aircraft either back to their bases or back into the fight unrepaired. A damaged aircraft sitting useless on the ground will be an expensive waste that cannot be tolerated when numbers are so few.

Before summing up, let me run over some points worth a mention that came up during my research among pilots operating present-day aircraft:

- a. the two man cockpit should be one totally integrated design project, not two;
- b. in two man aircraft, warning devices and vital indicators related to safe aircraft operation must be duplicated in both cockpits;
- c. the 30° seat rake in some modern aircraft can cause serious discomfort while attempting to look rearward under "g". Experience suggests no real advantage in less than 60° rake;

- d. navigators looking at their radars must be effectively alerted to critical warnings and other vital information by radar symbology;
- e. a limited number of switches or selectors with a vital or urgent function should be duplicated in the cockpit and if possible positioned clear of clutter from related equipment;
- f. / there should be more multi-function displays and more multi-function selectors;
- g. switches and selectors must be made more robust and capable of operation by pilots in full NBC kit;
- h. every effort must be made to reduce the number of layers of perspex a pilot has to see through;
- i. with ever increasing emphasis on the HOTAS concept, are we researching the development of pilots with 7 or 8 fingers on each hand, and if not why not ?

In summary, please remember Ravguy this week. We may no longer be able, or have enough flying time, to train him to the peak of perfection, but we can't afford to lose him at the outbreak of war, as we did in the past because we need his aircraft and we should also like him to live to become a veteran. It is his problems in the cockpit as he goes to war for the first time that you have got to solve. Please therefore make your quantum jumps slowly and inject operational experience and advice all along. New systems should reduce workload and cost, yet improve effectiveness, and must possess 100 % integrity. In 1981 pilots and planes are being lost in peacetime training because even the most modern cockpits, designed as integrated man/machine systems are still not sufficiently foolproof under high workload conditions. If we lose them in peacetime, what of our chances in war ?

Mr Chairman, as a guest and non-member of your panel, I have tried today to provide for you a keynote for what I am sure will prove to be a valuable and enlightening symposium. We all know that we stand on the brink of breathtaking progress into an exciting future. And I am sure I shall be expressing a world-wide sentiment by saying "Congratulations USA on your magnificent achievement of three weeks ago". To a pilot, seeing Columbia lower its gear and touch down so delicately after such an odyssey marked yet one more giant step for mankind. To me the event carried an extra poignance, for only a week or so earlier I had been scrutinising that unbelievably inhuman edifice the Berlin Wall and its associated paraphernalia of death-dealing devices. The contrast is somewhat akin to my keynote today. Technological advances in view offer us a new zenith in cockpit sophistication, but while our heads are high and maybe a little into the clouds, we must keep our feet on the ground and remember that for all of us here now, the ultimate goal is to enable our Alliance to deter an enemy possessing immense superiority of numbers. To succeed, in peace and in war, our military aircraft will have to be not too costly, not too complex and not too few.

Thank you.

HOW THE HELICOPTER COCKPIT DESIGNER USES DIGITAL AVIONICS

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SUMMARY

This paper presents an overview of the new approaches to helicopter cockpit design made possible through the application of advanced multiplex technology to cockpit displays and controls. This technology enables the pilot to have more information available while, at the same time, reducing his workload, and provides for substantially improved cockpit management. One of the major research programs through which this technology was tailored for military helicopters is ADAS (Army Digital Avionics System). This program is discussed, along with some new Bell helicopter cockpit designs.

INTRODUCTION

This decade is witnessing a revolution in the design of aircraft cockpits, a revolution whose goal is to supply more and more information to the pilot and crew within the space limitations of the instrument panel and cockpit, without creating a work overload. These new information needs have come at a time when the avionics state-of-the-art is able to accommodate both the pilot's needs and the cockpit size constraints. The resulting cockpits incorporate multimode displays controlled by advanced onboard computers and multiplexed system electronics. Already, high-performance fighters and fixed-wing transport aircraft reflect this revolution.

This paper discusses the impact of this revolution as it pertains to the helicopter cockpit. Problems unique to the helicopter are addressed in terms of pilot management techniques, display and control design philosophy, pilot and crew workload, and "hands-on" controls.

A review of helicopter cockpits employing multimode displays is also presented. Research projects now underway are discussed in which the entire helicopter cockpit has been designed to optimize the use of multimode displays and digital techniques. Examples are provided to demonstrate how system designers and human factors engineers work together to ensure optimum design. One example is ADAS.

The cockpit needs for missions performed by gunships, utility helicopters, and scout helicopters are reflected in the applications discussed. These new cockpits provide the pilot and crew with a flexibility never before contemplated. Quantities of data never before considered available are now at the pilot's fingertips. With these new techniques the flight crew is no longer forced to perform monotonous monitoring tasks, message decoding, time and distance computing, or performance calculations. The pilot and crew are now free to perform those tasks at which the human being can excel, i.e., decision making and problem solving. With this freedom comes the mission bonus of flexibility, improved accuracy of performance, and safety.

NEED FOR COCKPIT INTEGRATION

Traditional cockpit instrumentation, displays, and controls have reached such numbers that some system controls and displays are practically inaccessible to the flight crew. The proliferation of additional systems to enhance the helicopter's performance capabilities also adds significantly, not only to the size of the instrument panel and cockpit, but to the crew workload. Radical changes in cockpit design philosophy are now beginning to alleviate many of the cockpit management problems. Multiplex systems, coupled with the new cockpit design approaches discussed here, provide the basis for the revolutionary changes.

Reduced Crew Workload. A major reduction in crew workload can occur with the removal of routine housekeeping duties. The engineering development of flightworthy multiplex systems has provided the breakthrough needed to accomplish this task. The controllers of a multiplex system can transfer and/or process the information that is ordinarily monitored by the crew on a routine basis. Thus, they can be programmed to monitor the parameters that provide this information, perform trend analyses, and automatically alert the crew only when out-of-tolerance conditions exist.

The use of multiplex systems means that many of the existing dedicated instruments can be eliminated from the cockpit and replaced by such workload-saving techniques as the following:

- Automatic monitoring of helicopter system parameters.
- Automatic monitoring of out-of-limit conditions.
- Displays that show trends of operating conditions.
- Displays that alert crews to emergencies and changes in trends of system status.
- Synthesized voice recordings that report flight performance system status and emergencies.
- Synthesized voice recordings that read checklists and normal and emergency procedures.
- Effective use of pictorial symbology.

Improved flight safety will result from the automatic and continuous monitoring of aircraft system parameters for two obvious reasons. First, the recognition of an abnormal condition or trend will not depend on the crew reading and interpreting an instrument dial indication. Second, allowing the automatic equipment to assume these functions will reduce the amount of heads-down instrument scan time usually required of the pilot.

Multifunction Displays (MFDs). The multifunction display system provides great flexibility in the cockpit for presentation of information. Some of the major advantages in the use of MFDs are listed below:

- The format can be altered to accommodate different mission modes and changing mission requirements or to meet varying information display requirements.
- The required information is displayed in the centralized area of the cockpit, as opposed to the distributed sources in previous cockpit designs.
- The flexibility of the MFD, when integrated wisely with the helicopter mission requirements and onboard systems, can not only reduce pilot workload and fatigue substantially, but enhance flight safety and mission performance.

Advantages of Good Cockpit Design. The designers of the cockpit must consider:

- The human size and movement requirements
- The subsystems
- The crew complement

During the design phase, human factors engineers and helicopter system designers must work closely to develop good design concepts and ensure that those concepts are implemented throughout the entire cockpit. The benefits from such detailed engineering will be many, including reduced maintenance time and inventory requirements. Also, a net reduction in recurring costs should be achieved because of the reduced number of items to be installed and the reduced manufacturing (assembly) time.

INTEGRATED HELICOPTER COCKPIT RESEARCH

ADAS is a major design effort sponsored by the U.S. Army for the development of an integrated helicopter research cockpit (Ref. 1). The ADAS research program developed because of the concern over crew workload and information/management requirements in the Army's emerging tactical environment. This prompted the Army to investigate new avionics architectures for military helicopters. ADAS is a three-phase program designed to demonstrate the feasibility of using this type of architecture in Army aircraft.

Analysis Phase. The analysis phase of the program was conducted by Bell and included a study whose purpose was to define the characteristics of an adequate man/machine interface. The study included:

- Analysis of task requirements for the Army missions.
- Definition of data required by the crew.
- Design of cockpit displays and controls to fit system requirements of the testbed helicopter.

During the study, emphasis was placed on evaluating the specific needs that are peculiar to a tactical helicopter operating in a modern battlefield environment, including nap-of-the-earth (NOE) flight. The study included function and task analyses and analytically derived workload data. In addition, pilot surveys were conducted to define the integrated avionics configurations and cockpit management aids required for the man/machine interface.

The analytically derived data delineated crew duties and identified high or difficult workload situations that caused aircraft management deficiencies. Pilot surveys correlated actual operational requirements in the mission analysis with the analytical data. As a result of this analysis, new cockpit controls/displays and multifunction keyboards were interfaced with a 1553 multiplex system in various configuration studies. Controls/displays, designs, formats, and operation logic were specifically tailored, in both physical configuration and software design, for tactical helicopter requirements.

The helicopter selected for ADAS was the UH-60 Blackhawk. The conventional cockpit of the UH-60 was redesigned for the System Testbed for Avionics Research (STAR) integrated cockpit. The ADAS cockpit is shown in Figure 1.

Pilot Survey Data. A phase of the ADAS human factors engineering program involved establishing realistic pilot information requirements. To obtain these data a survey of active U.S. Army pilots stationed in operational units at Fort Hood, Texas, was conducted. Questions were directed to 34 active-duty pilots, all of whom were experienced in NOE flight. Experience in NOE flight was a requirement because flight under such conditions demands extremely high pilot and crew workloads.

The survey concentrated on data with respect to NOE flight planning, maneuvers, performance techniques, and control/display requirements. The results of the survey are summarized below:

Mission Planning and Execution

- Detailed premission planning is essential (navigation and performance).
- Mission changes are difficult to execute.
- Need exists for in-flight aids that help in navigation, performance management, and communication electronic operating instructions (CEOI).

Aircraft Management - Crews place high priority on information concerning

- Power management
- Navigation
- External hazards

Control/Display Priorities

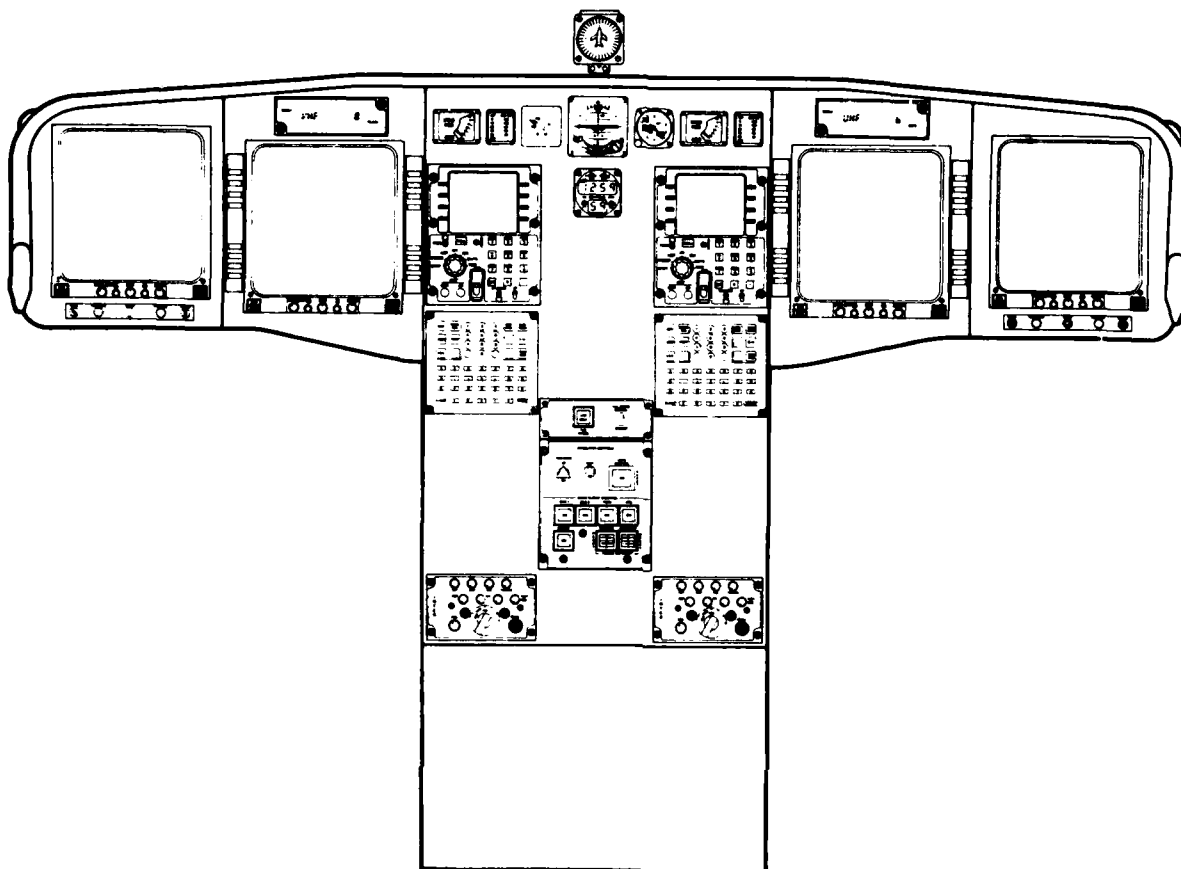
- Power management (torque)
- Heading
- Engine/transmission status
- Basic flight instruments
- Fuel
- Electronic navigation aids (does not include Doppler)
- Electrical systems

Cockpit Design. The Phase I cockpit configuration was the result of several design iterations, each of which was evaluated on the basis of physical layout (reach and viewing angles), redundancy, configuration management, and failure modes and effects analysis. Consideration was also given to night vision goggle compatibility and integration of the Army's night navigation pilotage (NNP) system. A wraparound console effect for the displays was selected for reach and viewing angles.

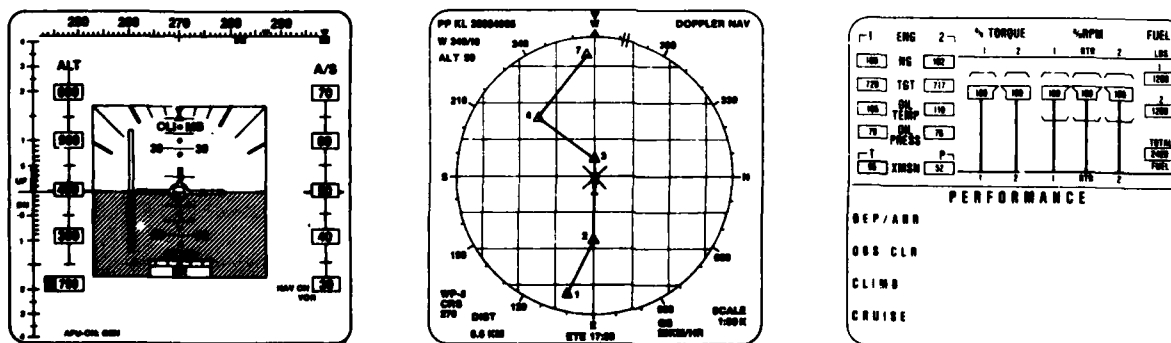
The configuration shown in Figure 1 consists of four multifunction Cathode ray tube (CRT) displays, with multifunction keyboards and interactive line-selects. Two integrated avionics communications controllers, furnished by the U.S. Army, are part of the total system. These are located in the center console.

System Operation. Control/display configuration, formats, and operation logic were designed specifically for tactical helicopter requirements. A combination of both branching and tailored software logic was selected to optimize data-retrieval time. This combination provides effective crew/systems interfaces with the management-by-exception techniques used for aircraft systems monitoring.

Display formats for the primary flight display use an integrated contact analog format, with different modes for hover, bobup, transition, and cruise. These displays are located on the outboard sides of the instrument panel.



Integrated cockpit instrument panel mockup



Typical ADAS information displays

Figure 1. The ADAS integrated cockpit instrument panel and typical information display formats.

The inboard displays are control and display units (CDUs). These units feature direct or automatic function access, with variable split-page formats and eight interactive line-selects on each side of the display. Functions integrated into the CDUs include the following:

- Interactive prestart and start procedures.
- Performance planning (departure, arrival, and dynamic).
- Doppler waypoint navigation map with tactical symbology overlays.
- Automated CEOI.
- Automatic and manual reconfiguration.
- Command instrument system (CIS).
- Airborne survivability equipment (ASE).
- Secondary systems (heater, de-ice, etc.).

The ADAS program has progressed from the human factors engineering and cockpit design phase to the equipment buildup phase. Sperry Flight Systems of Phoenix, Arizona, is building the system. The Army plans to initiate a hot bench development program early in 1982, with a full-up system integration checkout prior to the first test flight in early 1983.

EXAMPLES OF INTEGRATED HELICOPTER COCKPIT DESIGNS

The ADAS program is the first United States helicopter program committed to a digital integrated cockpit. It represents radical departures from the traditional concepts and, understandably, will meet with some opposition until helicopter pilots become more familiar with its benefits. There is no doubt, however, that the integrated "automated" helicopter will soon become the standard rather than the exception.

Transport Helicopter. An example of the evolution of an instrument panel with digital avionics, as envisioned for the BHT Model 214ST transport helicopter, is shown in Figure 2. This figure illustrates the nature of cockpit display/control changes that will occur as more advanced integration is used in the basic aircraft avionics systems design, starting with the incorporation of MFDs and progressing to the integration of full information displays.

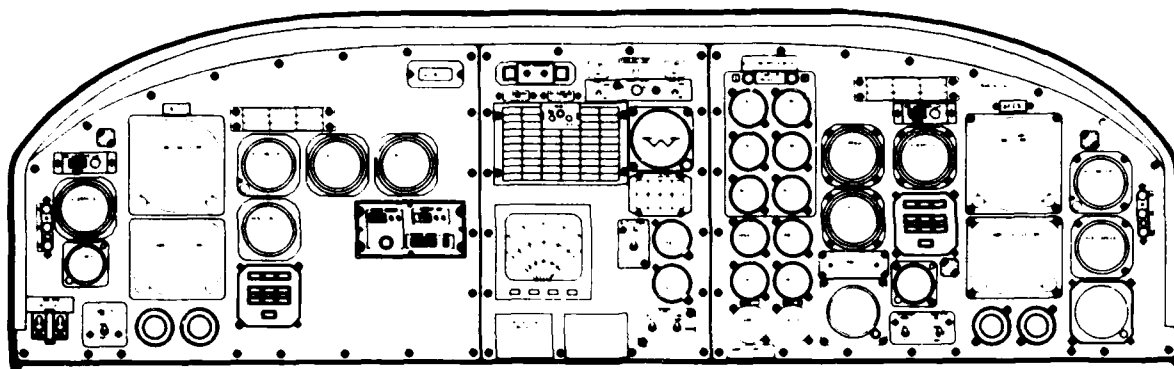
Scout Helicopter. Spectacular results have been achieved by Bell human factors engineers in the redesign of the Scout helicopter instrument panel using digital, integrated controls and displays.

Figure 3 shows the current instrument panel and center console of a Bell OH-58. Figure 4 shows the Bell Model 406 helicopter panel and center console, which were built on the basic airframe of the OH-58. The Model 406 is Bell's proposed Near Term Scout Helicopter for the Army. This helicopter employs a mast-mounted sight for day/night target acquisition and laser designation.

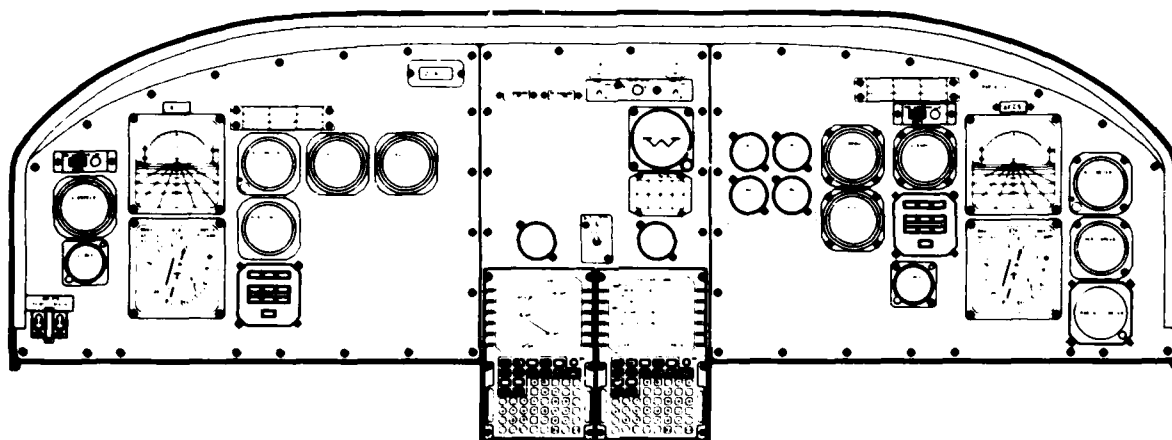
The Model 406 instrument panel was designed to preserve as much external visibility as possible by paralleling the instrument panel outline with the structural members of the forward end of the fuselage, as viewed from the pilot's station. As a result, almost no compromise to outside vision exists because of the panel. MFDs were placed high on the panel to minimize visual scan from outside to inside the cockpit. Also, the pilot has the ability to call up specific display modes for each maneuver, thus minimizing inside/outside scanning on a variety of flight segments. For example, during NOE he may want his map display in front of him and strategically placed for easy viewing. He may even want this display enlarged for peripheral viewing. On another mission, such as one with VMC conditions but where darkness and haze have obscured the viewing, he would want his attitude flight data in an easy viewing position.

There are two identical multifunction displays in the cockpit, one for the pilot and one for the copilot/observer (CPO). The MFDs are 8-inch diagonal CRTs. Each display has a bezel which contains software programmable keys and adjustment controls for the display. The two CRTs can display a variety of interactive information from the mast-mounted sight (MMS), communications, navigation equipment, flight sensors, and subsystems monitoring sensors with complete MFD flexibility, as well as display redundancy, for the crew. The Model 406 MFDs have the features shown in Figure 5 and listed below:

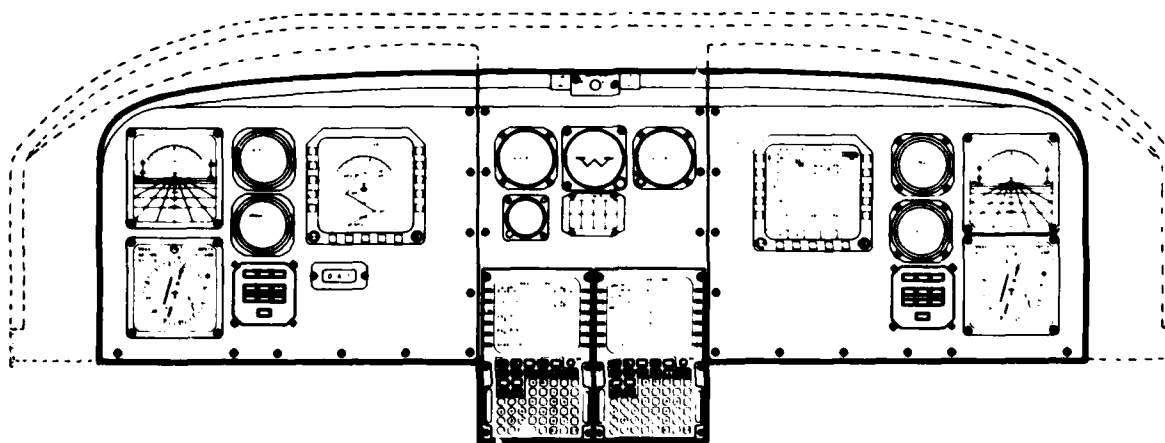
- Selection of a vertical situation display (VSD), a horizontal situation display (HSD), the MMS images, and communications (COM) control/status functions for both the pilot and CPO.
- Complete combinations of display modes simultaneously between the two MFDs, i.e., in single-pilot operation the pilot may make use of both displays if desired.
- MFD symbology and function redundancy sufficient to complete a mission in the event of a single display or symbol generator failure.



Traditional configuration



Incorporation of MFDs



Information display integration

Figure 2. Bell's 214ST helicopter instrument panel evolution with digital avionics.

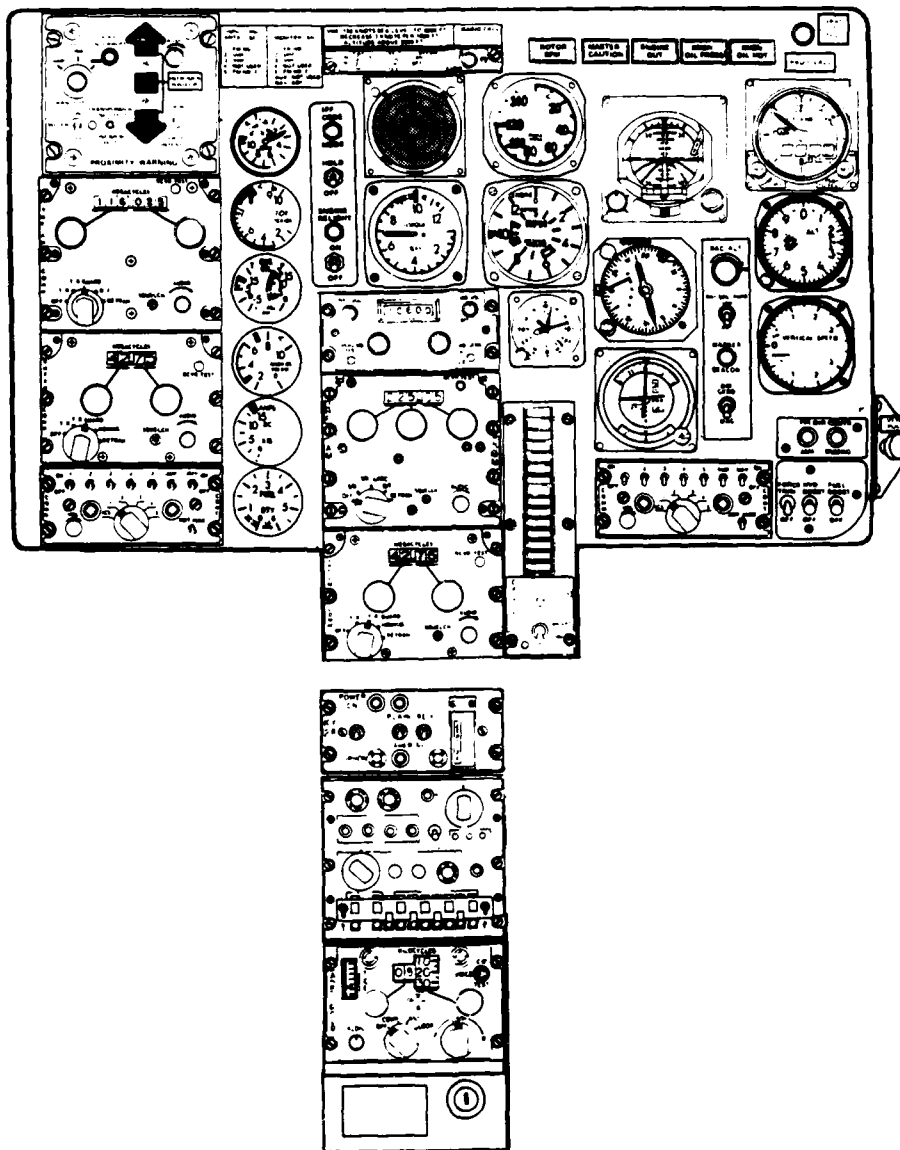


Figure 3. Instrument panel and center console of a Bell OH-58 helicopter.

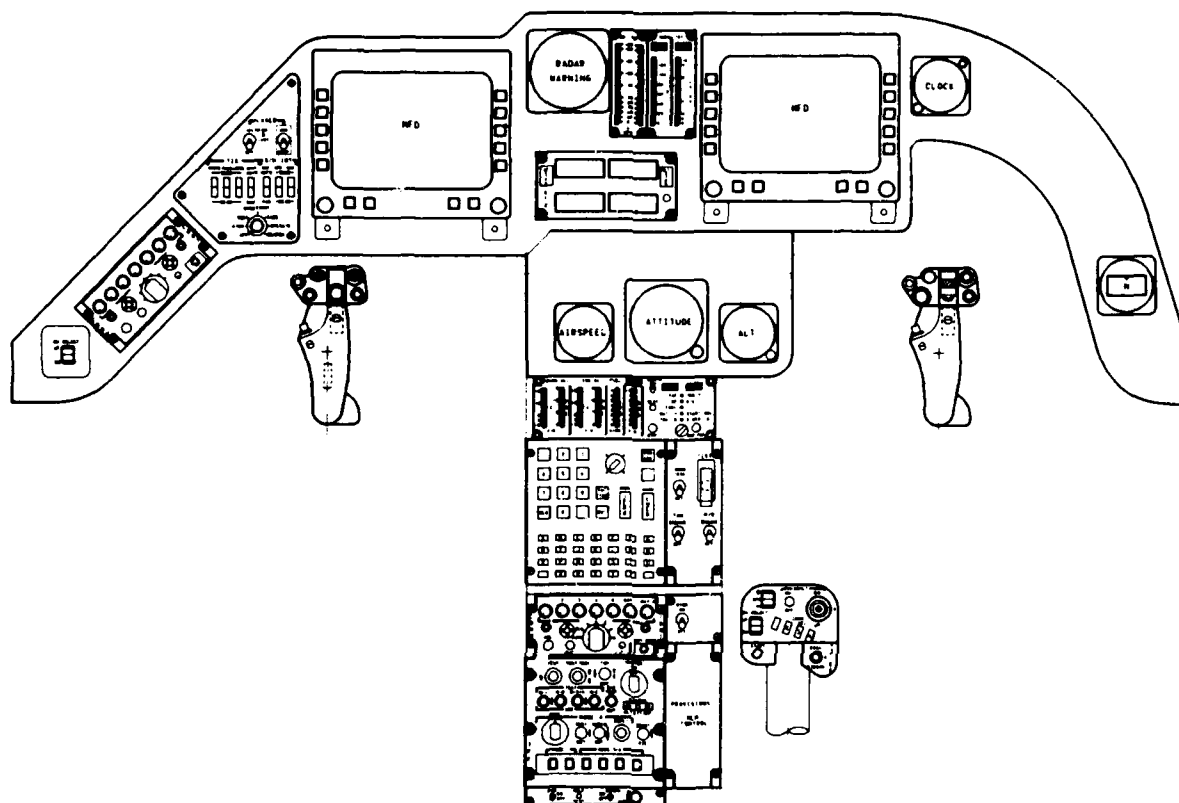


Figure 4. Instrument panel and center console of Bell's proposed Model 406 Near Term Scout Helicopter built on the basic airframe of the OH-58.

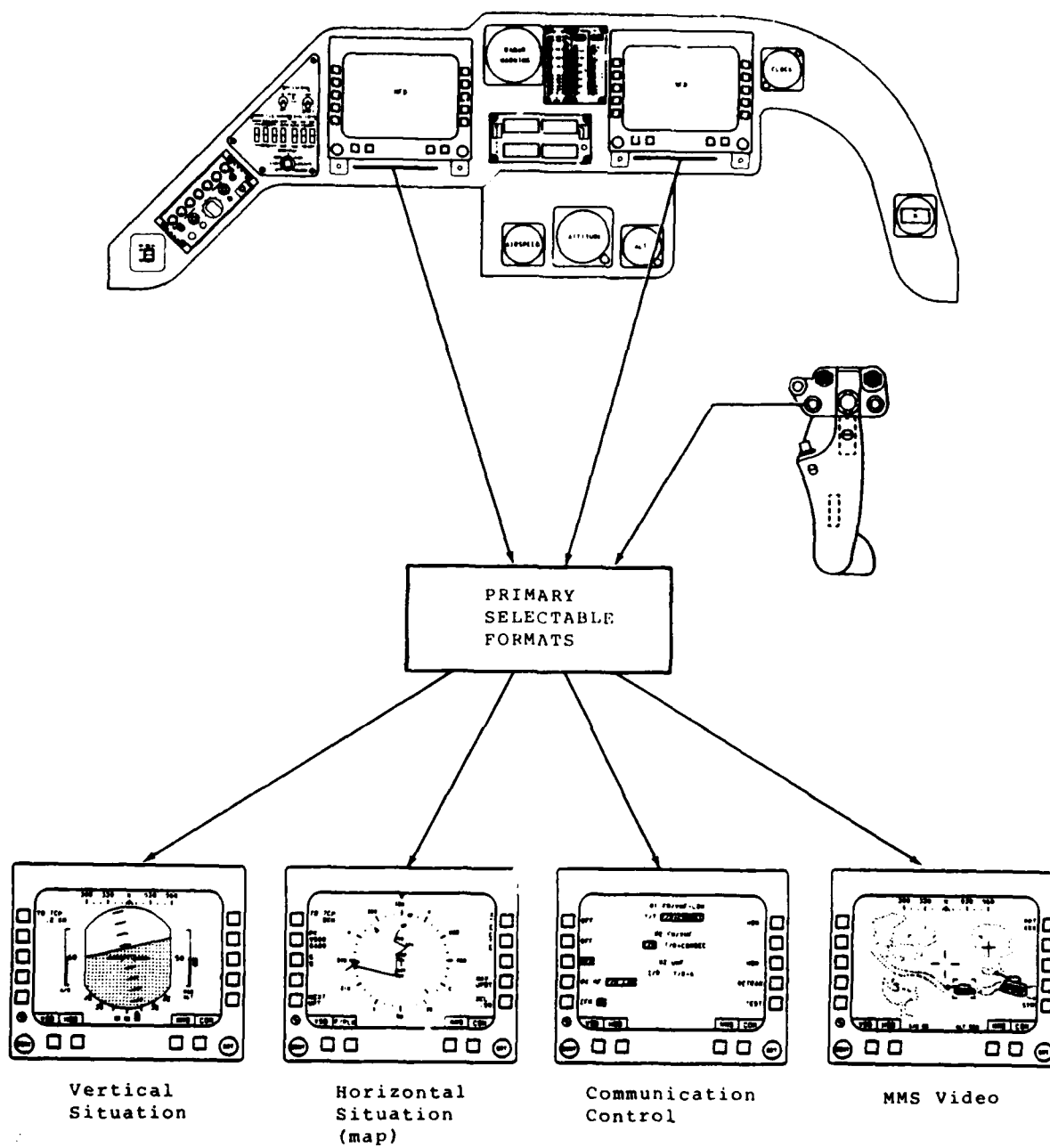


Figure 5. Primary modes selectable from MFDs.

Figure 6 compares the number of steps necessary to make a radio frequency change in the Model 406 with the operation of a standard radio control panel in the OH-58C. It is noteworthy that the entire operation is a "hands-on" procedure, i.e., a procedure in which the pilot does not have to take his hands off the primary flight controls. The information is displayed high on the instrument panel between the MFDs. Similar simplification is possible in the procedures to perform navigation functions and various types of MMS operations.

Attack Helicopter. Military attack helicopters using the integrated digital display concept are able to profit even more, since the data on weapon systems and fire control lend themselves well to MFDs. Figure 7 shows Bell's Modernized Cobra pilot cockpit as it is presently configured. A panel of the same size can be uncluttered by using two MFDs. In addition, the side consoles can be greatly reduced in size (see Figure 8).

CONCLUSIONS

The application of the multiplex technology to helicopter cockpit displays and controls has been made possible by the advances in electronics technology, primarily in the area of microprocessors and large-scale integration (LSI) techniques. Because of these advances, the size, weight, and cost to implement a multiplex system can be reduced to the point where it is uneconomical not to use multiplexing. Computer technology is no longer the limiting factor in cockpit design. Microprocessors have sufficient capability to allow the integration of multiple functions into single units; and the inherent redundancies in the multiplex system design, which are dictated by a conscientious design approach, add significantly to flight safety and mission reliability.

There are areas of design refinement that have not been fully explored, but which should be considered in future configurations. One feature is the use of colored displays. The extent of color utilization is a fruitful area of additional research which should be incorporated into the hardware evaluation of the overall program. Another potential cockpit aid is the use of synthetically generated, digitized, voice-warning systems incorporated directly into the MUX bus system and used to augment the visually displayed data. The new generation of voice-synthesizing systems is an attractive feature that should be evaluated.

Full utilization of the map display should also be explored for tactical flight-display use. At best, the present approach of map graphing is to ease the use of hand-held maps. Methods for dynamic annotation before and during flight would greatly enhance crew capability. A method for using the map display to update entries, record critical topographic features (such as wires and obstacles), and make tactical observations would further reduce crew workload during NOE flight.

REFERENCES

1. Ellis, James F. and Emery, J. H., "Army Digital Avionics System (ADAS) Human Factors Engineering Final Report," Volume II, Sperry Flight Systems Pub. No. 71-1662-80-02, December 1980.

TASK: CHANGE AN FM RADIO FREQUENCY AND TRANSMIT

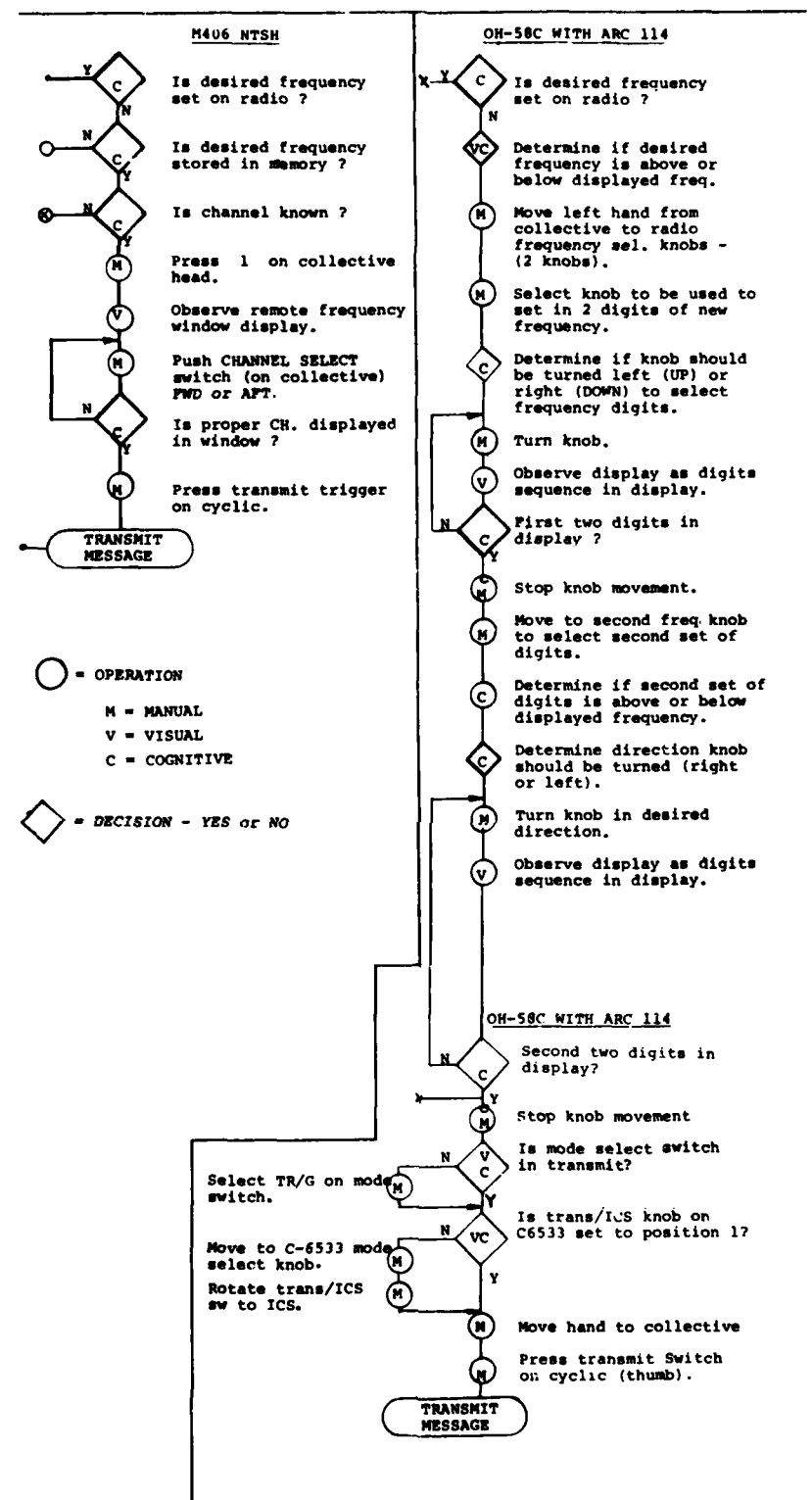


Figure 6. Task flow diagram: Model 406 vs conventional communications control panel.

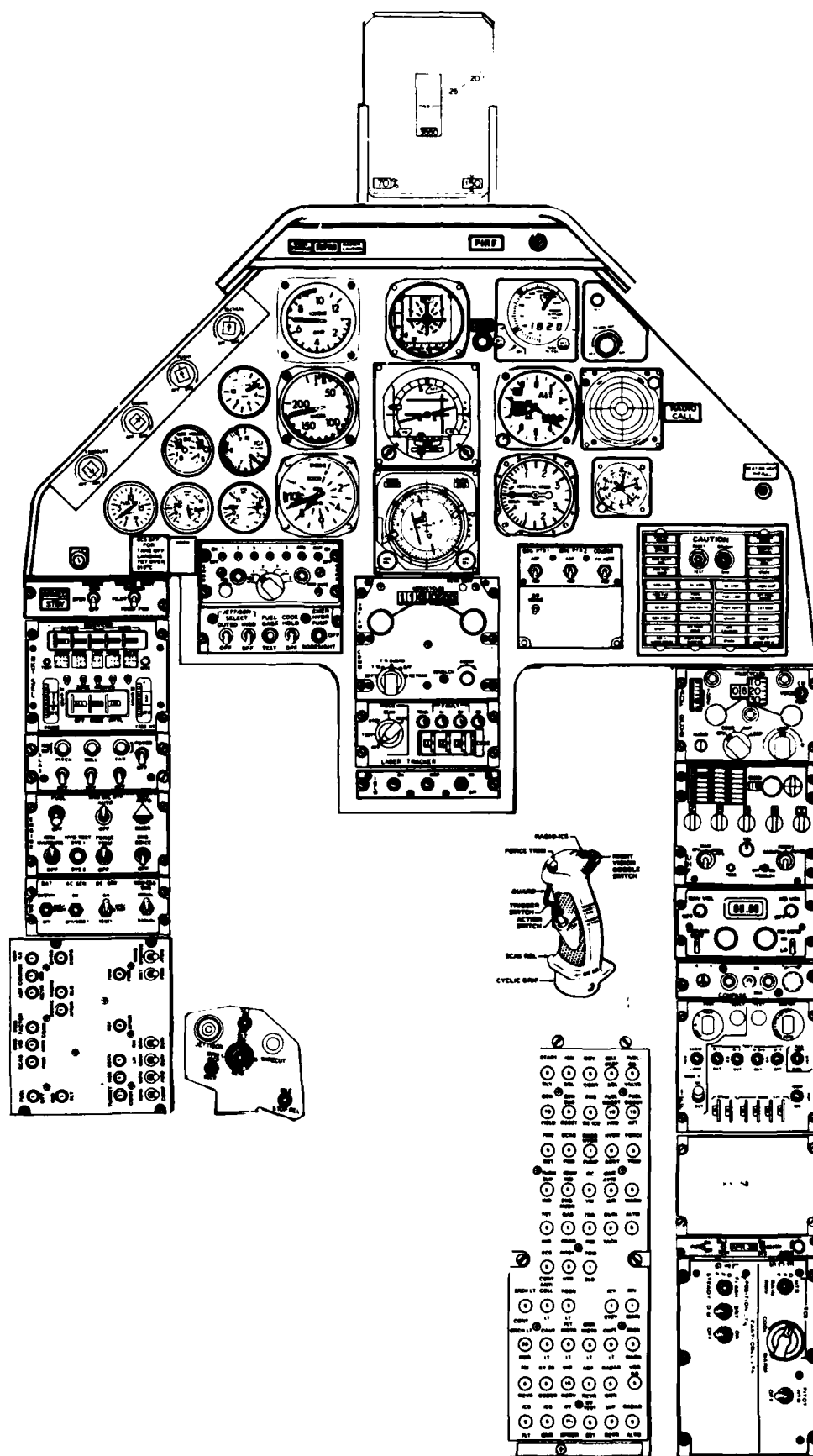


Figure 7. Bell's Modernized Cobra helicopter cockpit.

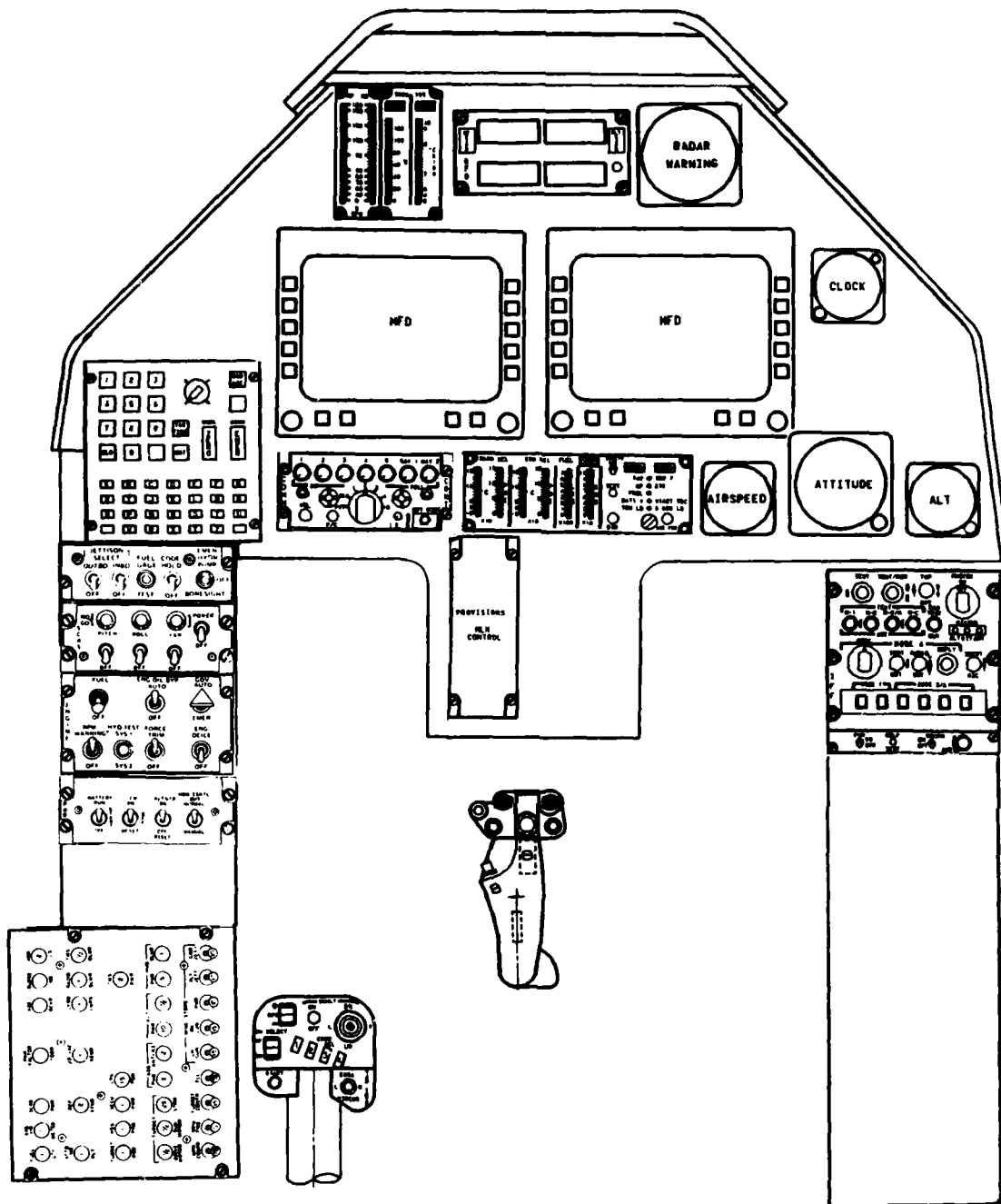


Figure 8. Sketch of a Bell Cobra helicopter cockpit demonstrating reduction in size of consoles and decluttering of panel by use of MFDs and integrated display techniques.

ELECTRONIC FLIGHT DECK DISPLAYS FOR MILITARY TRANSPORT AIRCRAFT

by

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SUMMARY

Electronic flight and systems information displays will shortly be coming into service in a number of commercial aircraft, and flight trials of a fully integrated electronic display system suitable for use in future generations of transport aircraft, will start early in 1981.

These display systems offer operational and economic advantages which can be realised in military as well as in civil aircraft. In particular, the flexibility of the display formats which can be provided, and the ease with which the information content can be changed, enable all the information required for the control of a transport aircraft to be displayed on the main panel, and go a long way towards making operation by a two-man crew possible.

In addition, the flexibility of an electronic display system makes it feasible to minimise the effect of failures within the display system to an extent which is impossible in the case of conventional instruments. Full realisation of this capability, which calls for careful selection of the system architecture to be employed, may lead to a significant increase in mission success.

INTRODUCTION

Electronic displays will form an essential part of the equipment installation of future transport aircraft, both military and civil. Displays being developed at present make use of colour cathode ray tubes (CRTs) as the display medium, and it is probable that these will form the basis of most transport aircraft displays for the foreseeable future. Although much effort is being devoted to the development of various types of flat-panel displays, primarily for use in domestic television receivers, it is likely to be many years before any such display device is developed to a stage where it can compete with the CRT in brightness, contrast, resolution, colour capability, and ease of addressing. Consequently, this paper will be confined to a discussion of CRT displays, although it is likely that for certain limited applications, where only alpha-numeric characters have to be displayed, matrix displays may come into use.

Until recently, CRTs capable of meeting the environmental requirements for airborne display devices were only able to produce monochrome displays, or by the use of the penetration phosphor technique, a limited range of colour. In the case of monochrome tubes a number of methods of generating displays have been used, from the various types of raster used for radar to the cursive (or stroke-written) generation used for head-up displays (HUDs). The former gave a display which was frequently too dim to see in bright daylight conditions without the use of a mask to exclude ambient light. The use of cursive generation enables very bright displays to be produced; these are obviously necessary for HUD applications, to ensure that the display can be seen against bright outside world backgrounds. Penetration tubes have generally used cursive generation, in the interests of minimising EHT switching complexity and of producing the brightest possible display; the maximum brightness which can be produced by this type of CRT is generally less than that obtainable with a monochrome tube.

During the last few years rapid developments in CRT technology have occurred, and these have led to the development of rugged shadow-mask colour tubes¹. These are robust enough to meet at least the requirements for transport aircraft, and may also prove to be capable of use in combat aircraft. Such tubes provide a full range of colour, and with cursive generation of symbols, the display is bright enough to see under all ambient conditions, when an efficient contrast-enhancement filter is used. Raster generation can also be used for such purposes as weather radar and shading of particular areas of displays.

Although the possibility of using monochrome CRTs for flight information displays has been discussed for many years, and much experimental work has been done in this area, the advent of colour displays has brought about a rapid swing in pilot opinion to the view that a full colour capability is essential when CRT displays are proposed as a replacement for conventional instruments. Among pilots who have become thoroughly familiar with what the new technology can offer, the view is already being expressed that, except in the standby role, conventional flight and navigation instruments are obsolescent, as far as large transport aircraft are concerned.

CURRENT ELECTRONIC DISPLAY ACTIVITIES

Three types of commercial transport aircraft being built at present will go into service in the next few years with a significant amount of flight, navigation, systems, and warning information provided by CRT displays. There are two main reasons for the

move away from conventional instruments: firstly, the cost of procuring and maintaining electronic equipment is decreasing relative to that involved in the case of complex electro-mechanical devices, because of the high level of labour with specialised skills which these require; secondly, the use of electronic displays for navigational information makes it possible to provide the crew with moving map displays on which can be superimposed the weather radar information, and this has operational advantages as well as possibly obviating the need for a dedicated weather radar display.

The electronic displays now being used for flight and navigational information form substitutes for the conventional attitude director indicators (ADIs) and horizontal situation indicators (HSIs); air data and other flight information are being displayed conventionally. The sizes adopted for the electronic ADI (EADI) and HSI (EHSI) are such that the conventional lay-out of the transport aircraft panel (with the ADI situated above the HSI) can be retained. Figure 1 shows the lay-out of a typical panel using this configuration.

It is interesting to note that in one of the current aircraft programmes, the primary display of airspeed and mach number has already found its way into the EADI, because of the various advantages offered by the flexibility of the CRT. In this aircraft, a conventional airspeed indicator is retained in its usual position in the panel, but is used only as a standby instrument.

In the areas of systems and warning information the current aircraft projects use CRT displays in slightly differing ways, but in general, one display is used in conjunction with a number of conventional indicators, to present the information required for control and monitoring of engines and aircraft systems such as electrical supply, hydraulics, pressurisation, etc. whilst the other CRT displays cautions and alerting messages. This second electronic display is backed up by conventional warning lights and audio signals.

It is clear that these display systems still use conventional instrumentation for a considerable proportion of the total information and considering the problems in gaining certification and pilot acceptance which might have arisen if an attempt had been made to proceed directly to a full electronic display system, it is not surprising that developments have occurred in this way.

However, on an experimental basis, work started nearly ten years ago on a programme aimed at investigating the feasibility and desirability of replacing virtually all the conventional instruments on the flight deck of a transport aircraft with CRT displays, retaining only the instruments required for standby purposes. This work was carried out at the British Aerospace plant at Weybridge, England, and led to the construction of a flight deck simulator² which was equipped with seven monochrome CRTs, providing raster-generated displays. Of these, two displays in front of each pilot provided primary flight and navigational information, and three units in the centre panel supplied engine, systems, and warning information. Because of the size of the displays (approximately 200 mm x 150 mm) it was necessary to install the primary flight display (PFD - attitude, air data and heading scale) and navigation display (ND - compass display or electronic map and radar) side-by-side, instead of in the conventional positions with the PFD above the ND. Pilot acceptance of this configuration, with its consequent modification to the normal scan pattern, was one of the aspects of the display system subjected to particularly close scrutiny during the trials in the simulator.

As a result of providing a full range of CRT displays, with their inherent flexibility of information content, it proved possible to configure the simulated flight deck so that all controls and displays were within the reach of the two pilots, and the Flight Engineer's station was eliminated. The resulting workload on the pilots was another subject of close scrutiny.

The result of extensive trials in the simulator was that there was general agreement that the basic concept of this type of display system and flight deck lay-out was sound (though it was generally felt that only two systems displays (SDs) were required), that the side-by-side positioning of the PFD and ND posed no particular problems to the pilots, and that the technical feasibility of operating a large transport aircraft with a two-man crew was established.

The next stage of the development of the Advanced Flight Deck was to confirm the results of the simulator experiments with flight trials, and it was agreed that a BAE 1-11 aircraft operated by the United Kingdom Ministry of Defence at the Royal Aircraft Establishment, Bedford, England, should be used for this purpose. It was originally proposed that the displays should be raster-generated on monochrome CRTs, giving close similarity with those used in the simulator, but during the early stages of the development of the flight trials hardware, rugged shadow-mask colour CRTs became available, and it was decided that the final installation must incorporate tubes of that type. The monochrome displays were completed, and used for checking out the aircraft installation and for initial flying, but the system was designed so that display units could be changed, and so that minimum modifications to symbol generators would be necessary, as soon as colour display hardware was available.

Consideration of the possibility of reducing the number of CRTs in a complete system to six (two PFDs, two NDs, and two SDs) led to the proposal for a panel lay-out of the form shown in Figure 2, enabling the display unit size to be increased to 200 mm x 200 mm. For the first stage of the flight trials programme, only the PFD and ND at the Captain's position are installed, the existing instrumentation being retained at the

First Officer's position and in the centre panel. Figure 3 shows a block diagram of the experimental installation in the BAe 1-11. Being a relatively old aircraft, it is equipped with a very varied collection of sensors which supply data in a wide variety of formats, and a separate interface unit has been provided, to accept all the sensor signals and convert them to the serial digital format (ARINC 429) required for the input to the symbol generators; this unit would not be required in a modern aircraft, in which the interfacing would be accommodated within the symbol generators. One symbol generator drives the PFD and the other drives the ND, but each symbol generator has the ability to drive both displays, if necessary, and the full display capability is retained even if one generator fails.

An external core-store and a paper tape reader are provided so that changes in display formats can be made during the flight trials, without removing the equipment from the aircraft. Interfacing with a general purpose computer in the aircraft is provided to enable the display system to be used in conjunction with an area navigation system being used in concurrent flight trials.

Operation of the aircraft with monochrome display units started in 1980, and the colour displays will be in use in the summer of 1981.

DISPLAY SYSTEM CONFIGURATION

An advanced flight deck display system can be configured in a number of different ways, depending on the performance capability of the individual units of the system and on the scale of redundancy required. A typical architecture for the flight and navigation information subsystem is shown in Figure 4. This is based on Symbol Generator Units (SGUs) capable of accepting multiple data inputs from the aircraft sensors and able to generate two separate display formats (PFD and ND) simultaneously. The display units are each capable of accepting inputs from either of two SGUs. Discrete signals from the pilots' control panels (P1 CP and P2 CP) select the data source to be used by each SGU, and the SGU to provide the display data for each display unit.

In the normal configuration, both the Captain's displays are fed from SGU 1 and the First Officer's from SGU 2; one set of sensors feeds SGU 1 and the second set feed SGU 2. In the event of failure of either SGU 1 or SGU 2, SGU 3 can be switched in to take its place, with its data source selected appropriately. In addition to the flexibility provided by this configuration, provision can be made for the data fed to the two pairs of display units to be reversed, so that the PFD and ND are reversed. This facility enables either tube to be time-shared between the two display formats in the event of failure of the other tube; it is controlled by a discrete signal from the PCP.

This system configuration provides maintenance of full display facilities after the failure of a SGU or of a data source, and leaves each pilot with access to all display data, by time sharing, after a CRT failure.

Figure 5 shows a possible configuration for the systems and warning displays, in which each SGU normally drives one display unit but is capable of driving both in the event of failure of the other SGU. The arrangement of the inputs to the SGUs depends very much on the particular form of warning system adopted for the aircraft, but is likely to involve warning computers which provide outputs to both SGUs. Engine and systems information is likely to come via data converters which change the large number of separate sensor signals to a common serial digital data format.

UNITS OF ELECTRONIC DISPLAY SYSTEM

General

Display system hardware currently being proposed for military transport aircraft applications is generally designed to conform to the civil requirements defined by ARINC Characteristic 725. This lays down interface and equipment form-factor requirements based on the current state-of-the-art, and it may require amendment in the light of future developments. At present, it leads to a useful degree of standardisation of equipment without inhibiting developments required for specifically military applications.

Display Unit

For the flight trials in the BAe 1-11 aircraft described above, display units designated Form Factor 'D' in ARINC 725 are used. These units have overall dimensions of 200 mm x 200 mm x 355 mm, and incorporate a CRT which provides an active display area of 165 mm x 165 mm. For installations requiring smaller display units, other sizes, such as ARINC Form Factor 'C' (160 mm x 160 mm x 355 mm, giving an active display area of 125 mm x 125 mm) are available.

The rugged shadow-mask tubes used in these display units typically have a resolution of approximately three colour triads per millimetre (about three times the resolution of the tube in a domestic television receiver), each colour dot being approximately 0.1 mm in diameter. The interstices of the screen are normally matt black, giving a low reflectivity to ambient light, and therefore improving the contrast of the display. Further contrast enhancement may be provided by an externally-mounted filter. Both delta and in-line electron gun configurations have been used for these CRTs; the in-line arrangement is generally accepted as enabling simpler methods of convergence correction to be used, and giving better spot definition.

Figure 6 shows a block diagram of a typical display unit. It has provision for dual deflection, video and chrominance inputs, to allow for connection to two separate SGUs, and selection between the two is by means of a discrete from the PCP. The deflection signals are shaped to provide the necessary screen geometry correction, and are fed to the deflection amplifiers. When operating in raster mode (for radar display, for example) an energy recovery circuit will be switched into operation, providing fast fly-back for the appropriate deflection signal with minimum power penalty. Convergence correction is derived from the deflection signals via a matrix, and operates on the convergence yoke of the CRT. Writing speeds of approximately 1 mm/microsecond in stroke writing and 3 mm/microsecond in raster, are achieved.

Video and chrominance signals are fed to a microprocessor, together with inputs from a display brightness control on the PCP and from ambient light sensors fitted on the front of the display unit case. The microprocessor controls the operation of colour selection and video drive circuits. A phosphor protection system is provided, which blanks the display in the event of faults such as failure of the deflection system, which would otherwise be likely to result in burning of the screen.

All the power supplies required in the display unit are derived from the aircraft 115 V 400 Hz single phase supply. The power dissipation is typically in the region of 100 W, and provision is made for cooling by means of air which is arranged to circulate round the CRT neck components and the electronic circuit blocks grouped in that region.

Symbol Generator Unit

Figure 7 shows a block diagram of a typical SGU. For the civil market, such a unit is contained in a 6 MCU case as defined by ARINC 600, with overall dimensions 190 mm (W) x 194 mm (H) x 318 mm (L). It has provision for forced cooling, and dissipates approximately 110 W. The mass of the unit is less than 10 kg.

Provision is made for dual inputs of data in each of three formats - serial digital (ARINC 429), discrete signals, and high speed digital data from weather radar equipment. Selection between the dual inputs is made by means of discrete signals from the PCP. The digital inputs are decoded and checked for transmission integrity and are then loaded into a buffer store; the processor extracts the information from the store and manipulates it into a form suitable to drive the vector generator. Deflection and bright-up signals, together with colour descriptions for the symbols in the cursive part of the displays, are produced by the vector generator, which also generates the outline of the sky/ground shading of the PFD and writes it into the flight display video memory.

The selected weather radar input is decoded and passed to a processor, where it is converted from the polar co-ordinate form in which it is transmitted to the cartesian form in which it is displayed, and is also scaled and combined with aircraft heading and groundspeed data, and stored in the navigation display video memory.

The digital outputs from the vector generator and the two video memories are time multiplexed to produce the flight and navigation displays. Two buffered outputs of each display format are provided, so that it is possible to drive four display units (in two pairs) from a single SGU.

The cursive symbology in the displays is refreshed at 80 Hz, and the 2 : 1 interlaced raster used for the sky/ground shading in the PFD and the weather radar overlay in the ND is refreshed at 40/80 Hz. Cursive symbology can be called up in any one of fifteen colours, and raster areas of the displays in seven colours.

Pilots' Control Panels

The form of control panel used in an electronic display system depends upon the particular system configuration which is used, but certain functions are necessary for all types of system. These include controls for overall display brightness, brightness balance between cursive and raster parts of display, map/compass rose, map scale and radar range, radar on/off, decision height selector, and test mode.

DISPLAY FORMATS

General

Much ground-based work to establish optimum display formats has already been carried out in a variety of simulators, but there exists a relatively small amount of experience in the use of advanced displays actually in flight. It is to be expected that as flight experience builds up, some modifications to display content and to the shape and colour of symbols may be required. It is at the same time the great advantage of an electronic display system (to the operator) and the great disadvantage (to the hard-pressed engineer) that such changes can be effected late in the development of a system without disastrous costs for re-design and re-installation of hardware.

The total amount of information in each display clearly depends on the area available, and as has already been stated, the relatively small displays shortly going into service in commercial aircraft have to be supported by a significant number of conventional instruments, whereas the large displays being evaluated in the BAe 1-11 aircraft require only a small number of stand-by instruments.

Primary Flight Display

The format used in the 200 mm x 200 mm display in the BAe 1-11 is shown in Figure 8. This shows how the basic T-configuration familiar to all transport aircraft pilots is provided, although the full navigation display is located at the side of the PFD rather than below it. The forms of the individual parts of the display have deliberately been made to resemble those of conventional instruments, to minimise the familiarisation period for pilots transferring to the new display system. At the same time, a number of features are provided which are only possible because of the flexibility of the CRT display. These include a full range, single scale, single pointer airspeed indicator, with a sensitivity of 100 kt per revolution of the pointer, limit speed data which are only in view during the appropriate phase of the flight, and specific indication as to whether the datum setting for the altimeter is QFE, QNH, or standard.

Colour is used, in addition to position and pattern, to differentiate between the various types of information in the display. Thus, at the present state of development, white is used for elements indicating the present performance of the aircraft (speed, height, etc) magenta is used to indicate selections made by the pilot (selected speed, height, heading, etc), green is used for fixed scales, and red for warning information. Pictorial parts of the display are presented in traditional colours; for example, an amber aircraft symbol is used in the attitude display, together with blue 'sky' and brown 'earth'.

Full information is given of the state of engagement of the autopilot/flight director and auto-throttle systems, showing both armed and engaged modes. In the case of an aircraft equipped for automatic landing, the landing phase indicator would also be incorporated in the PFD.

Smaller sizes of display are generally similar, though with a restricted information content. Figure 9 shows a typical 180 mm x 150 mm PFD.

Navigation Display

Figure 10 shows the BAe 1-11 ND in the map mode. The same conventions have been adopted for the use of colour as in the PFD. The weather radar return can be overlaid on the map, giving an immediate indication of the position of storm activity relative to the planned flight path. The scale of the map and the range setting of the radar are selected by a single control on the PCP to ensure compatibility at all times. In the electronic display systems currently under development, the storage and processing of the data required for the construction of the map display is carried out in the flight management system rather than in the display system.

Full details of the operation of the radio/navigation system are given in alphanumeric form at the sides of the ND. These include selected frequencies, waypoint data, and time and groundspeed information.

In the compass rose mode, selected on the PCP, the centre part of the ND provides heading and radio/navigational information in the same format as in a conventional horizontal situation indicator.

Systems Displays

Since the experimental display system installed in the BAe 1-11 aircraft at present includes only the PFD and ND in the Captain's panel, less detailed work has been carried out in the systems display area than in the case of the other displays. However, preliminary studies have generated various display formats, of which Figure 11 shows an example. This is a display of primary engine information for a 2-engine aircraft, together with performance monitoring data for main aircraft systems.

It is perhaps in the systems area that the flexibility of the CRT display becomes most useful, since it enables detailed information on the state of any of the aircraft systems to be displayed on demand. It is also possible for the appropriate format to be displayed automatically in the event of a malfunction, so that corrective action can be initiated with minimum delay.

Caution and warning information (which will be displayed on the second Systems Display) is processed so that in the event of multiple warnings (such as would occur in the event of an engine failure) the appropriate priority order for corrective actions can be indicated in the display.

HUMAN FACTORS

When CRTs were first considered as a possible means of displaying flight information to pilots, doubts were expressed as to their acceptability from the human factors point of view. Although flight experience with these displays is limited, there are no indications that any serious problem exists. Various studies of human factors aspects of airborne CRT displays, have been made^{3,4}, and these have provided ground rules for the design of the equipment for evaluation in the BAe 1-11 aircraft.

The rate at which a CRT display is refreshed must be considered carefully, in order to avoid perceptible flicker, which is likely to be most apparent in display units viewed peripherally. The actual refresh rate that is acceptable depends on the particular phosphors used in the CRT screen; short persistence phosphors require a

higher refresh rate than long persistence types, to avoid flicker. In the case of phosphors of the P22 type commonly used in colour CRTs for airborne displays, a 50 Hz refresh rate is satisfactory for most observers, and the 80 Hz rate commonly used provides a wide safety margin. The higher frequency also reduces the noticeability of the jump effect (which is in any case not perceived by all observers); this is manifested as an apparent movement of the display when the observer's point of fixation scans across it, and is due to the interaction between the moving fixation point and the refresh pattern of the display. The effect is not peculiar to colour CRTs, and may be detected by some observers in any periodically refreshed display.

It is frequently suggested that the use of a large number of CRT displays in the flight deck may cause additional crew-fatigue problems; a number of lengthy operations carried out in the BAe simulator failed to produce any evidence of this.

Much work has been carried out on the use of colour in CRT and other displays, and many of the associated perceptual problems have been studied in some detail⁵. Typical of these is the apparent change in the perceived colour of a display element with changing display luminance, ambient conditions, and state of adaptation of the observer. It will be impossible to say with certainty that the solutions found to these problems are fully satisfactory until equipment of this type has been in service for an appreciable period of time. One of the functions of the micro-processor in the display unit, described earlier, is to adjust the colour content of the display in such a way that the subjective brightness and colour contrast between different elements of the display remains balanced over the whole luminance range of the display.

Any light emitting display must have its brightness varied when the ambient illumination changes, if uniform display contrast is to be maintained, and in the case of airborne CRT displays this is done by an automatic system controlled by signals from sensors mounted on the front of the display units. In addition, to counteract the effect on the pilots' eyes of high light levels outside the aircraft (such as sunlight reflected off white clouds) an additional input to the automatic brightness control system can be provided from a forward-looking sensor.

Although the screens of the CRTs used for airborne displays normally use pigmented phosphors in a black matrix to minimise reflectance of ambient light, it is still necessary to provide some form of optical filtering to ensure adequate display visibility under all conditions. In single-seat cockpits directional mesh filters provide useful contrast enhancement, but the acceptance angle of this type of filter is inherently low, and makes it unsuitable for use in a transport aircraft, where cross-monitoring between Captain's and First Officer's displays must be possible. The simplest form of filter for this application is a neutral density type, which provides twice as much attenuation of unwanted ambient light as it does of the light emitted by the CRT. An alternative approach, also suitable for wide-angle viewing, is to use an absorption filter with three pass bands arranged to match the wavelengths of the principal emissions of the three colour phosphors. Such filters provide a somewhat higher performance than the neutral density type, but currently at higher cost. Any filter which is used requires to be bonded on to the CRT face, and to have an anti-reflection coating on its outer surface, in order to minimise the effect of the additional, potentially reflecting surfaces.

Application of available technology has made it possible to design and manufacture colour CRT displays which should be capable of meeting all the requirements imposed by human performance capability. If extensive flight experience shows that modifications are desirable in such areas as the colour or shape of particular symbols, these can be effected, as has already been pointed out, without major hardware changes.

MILITARY REQUIREMENTS

In general, the operation of a transport aircraft in a military rather than in a civil environment is likely to reduce the availability of navigational data, rather than having much effect on the display system itself. Whilst in peacetime military transports may make considerable use of the civilian air traffic control system and navigational aids, in wartime the requirement will be for self-contained navigation without reference to ground-based aids. In each case, the information displayed to the pilots will be very similar, although there may be requirements for additional symbols in the NDs for designating the positions of features of military interest.

The introduction of data link systems may call for the introduction of an additional CRT for the display of data received through such channels, if the volume of traffic warrants it; initially this data could probably be accommodated in one of the SDs. There may also be a requirement for a teleprinter, to provide hard copy of data to which reference may have to be made repeatedly over a period of time.

There is likely to be a requirement for additional flight information during such operations as low level supply dropping; such information is likely to be similar to that required in order to make precise approaches to non-instrumented landing strips, and may require a head-up as well as a head-down display.

It has been suggested that there may be problems in military aircraft using large numbers of light emitting displays from the point of view of the amount of light visible at night from outside the aircraft. It is probable however, that less light will be emitted from a flight deck with CRT displays than is scattered by the integrally lit instruments of a conventionally-equipped aircraft.

The main difference between the display systems for military and civil transports may well prove to be the different environmental capability demanded by operations from rough and semi-prepared fields. Equipment already available is likely to be able to meet these requirements fully.

ADVANTAGES OF ELECTRONIC DISPLAYS

As has been stated earlier, there are both economic and operational advantages in equipping a transport aircraft with CRT displays.

From the economic point of view, an electronic display system already offers an advantage over conventional displays in cost of procurement; a recent study indicated a saving of more than 30% in the cost of a complete display installation for a large transport aircraft. It is likely that a similar, or greater, saving in cost of ownership will be achieved, since electronic displays are amenable to a high degree of automatic testing, and require a relatively small amount of highly skilled labour for their maintenance.

In addition, application of the flexibility of electronic displays provides the possibility of configuring the flight deck for two-man operation, the economic advantages of which may be of more value in the military environment than in the civil, where there is strong opposition to the two-man crew concept from many pilots' unions.

This same flexibility provides the main operational advantage of the electronic display system: information in which the pilot is not currently interested can be suppressed from the displays. Whereas in the past the pilot has been confronted with all the information all the time, and has had to filter out mentally the items in which he is interested, it is now possible to effect at least some of this filtering by suitable organisation of the programming of the display symbol generators, which has the effect of reducing the pilot workload. There is also the advantage of being able to integrate information, such as route and weather radar data, in a way which has not been possible previously.

A further advantage which arises from the flexibility of electronic displays is that all information is still available to the pilot, on a time sharing basis, after the failure of one display unit. In a conventional display system, in the event of failure of an instrument, the information it provides can only be obtained from the corresponding instrument on the other side of the flight deck. The two types of display system can be made comparable in their ability to withstand the effects of failures of data sources and processing devices with minimum inconvenience to the crew.

Thus both operational and economic considerations favour the introduction of electronic display systems, and the economic balance is likely to come down even more firmly in favour of the advanced displays in the future than it does at present.

CONCLUSION

Transport aircraft instrumentation is on the point of taking what is probably the biggest single step forward that has happened in the whole history of flying. From the earliest days of flying until the present day, virtually all the information available on the flight deck has been presented by mechanical and electro-mechanical devices. Now, within the space of a few years, CRT displays will be appearing in ever-increasing numbers of aircraft, both military and civil. Initially only a limited amount of information will be displayed electronically, but that amount includes much of the information that is vital to the safe and efficient operation of the aircraft.

It seems likely that not many more years will pass before the flight deck fully equipped with electronic displays goes into service. This will realise to the full the operational and economic advantages which modern display technology can offer.

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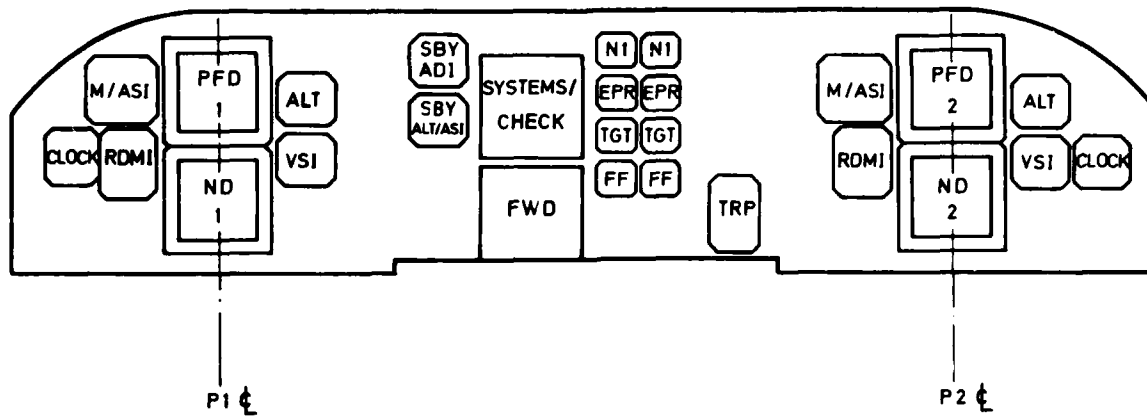


FIG.1 INSTRUMENT PANEL WITH PARTIAL ELECTRONIC DISPLAY SYSTEM

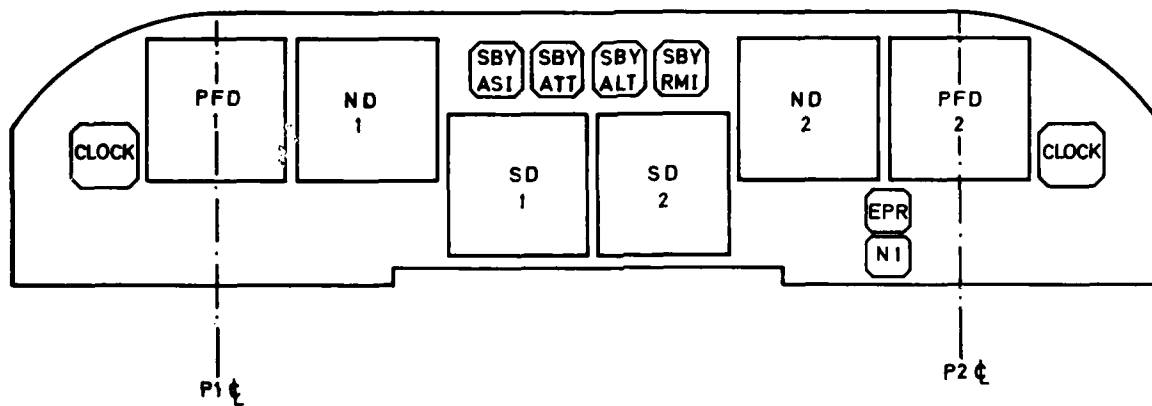


FIG.2 INSTRUMENT PANEL WITH FULL ELECTRONIC DISPLAY SYSTEM

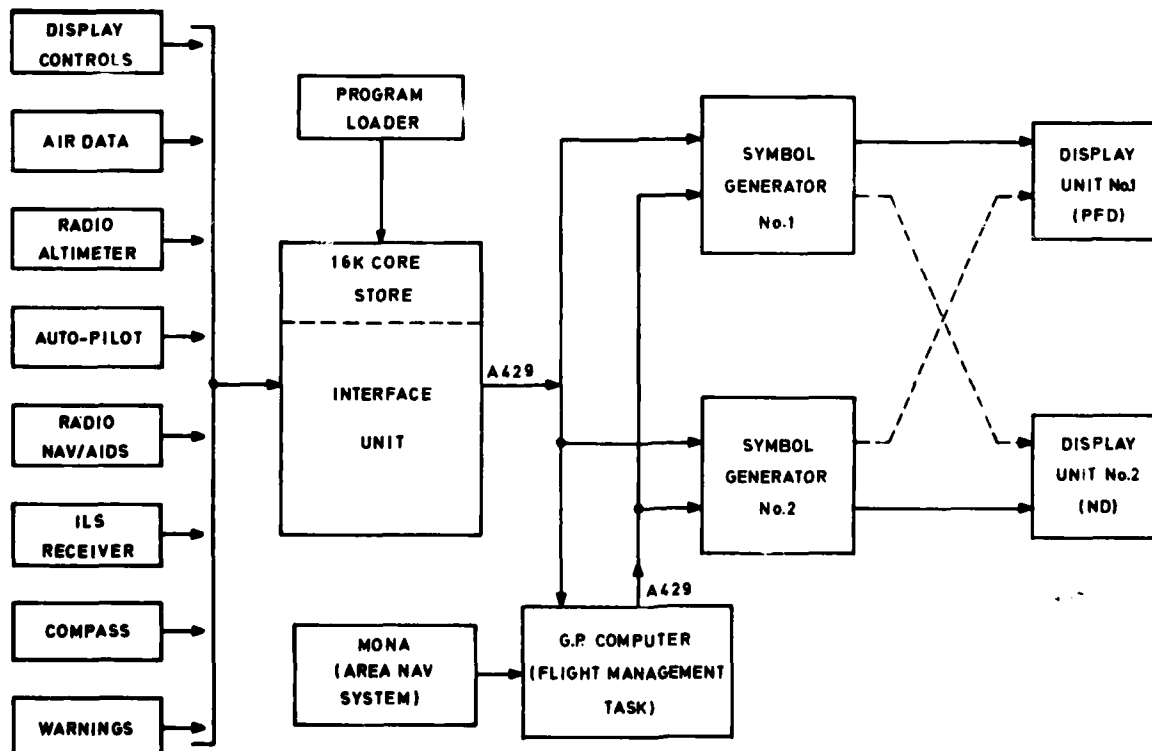


FIG.3 EXPERIMENTAL ELECTRONIC DISPLAY SYSTEM IN BAe 1-11 AIRCRAFT

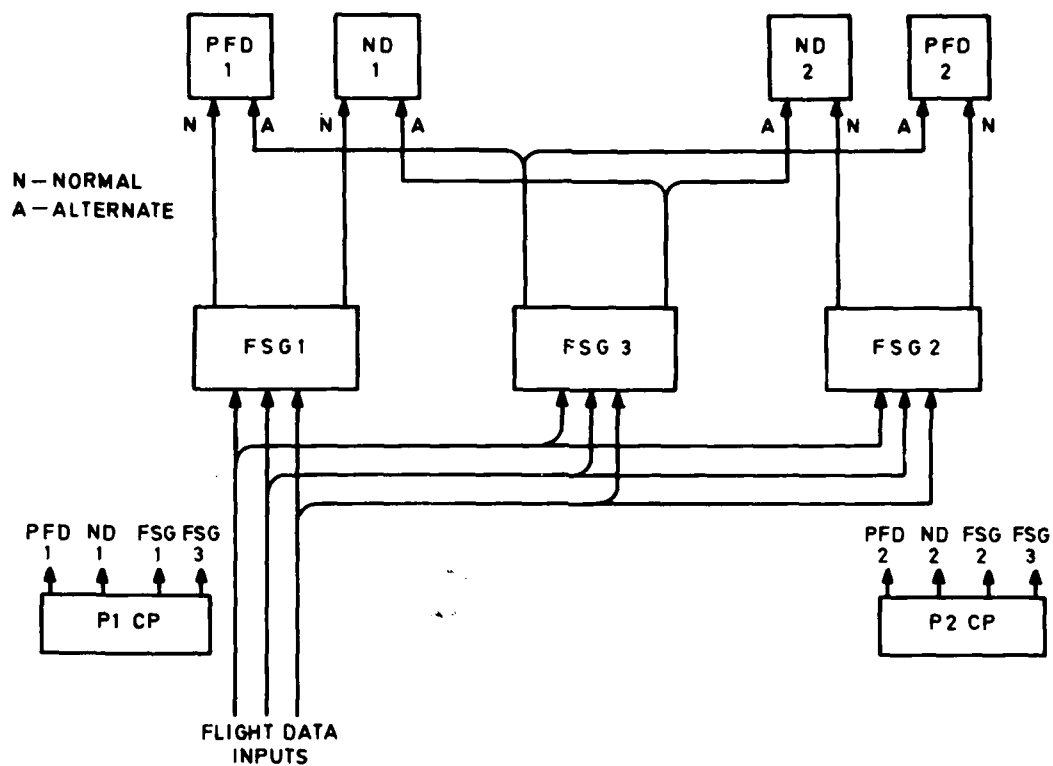


FIG. 4 FLIGHT AND NAVIGATION DISPLAY SYSTEM ARCHITECTURE

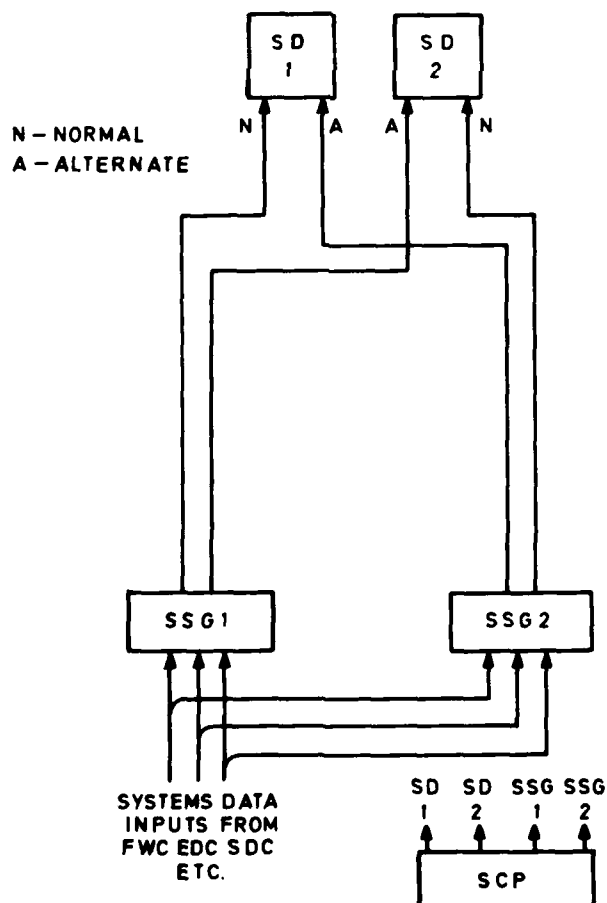


FIG. 5 SYSTEM AND WARNING DISPLAY SYSTEM ARCHITECTURE

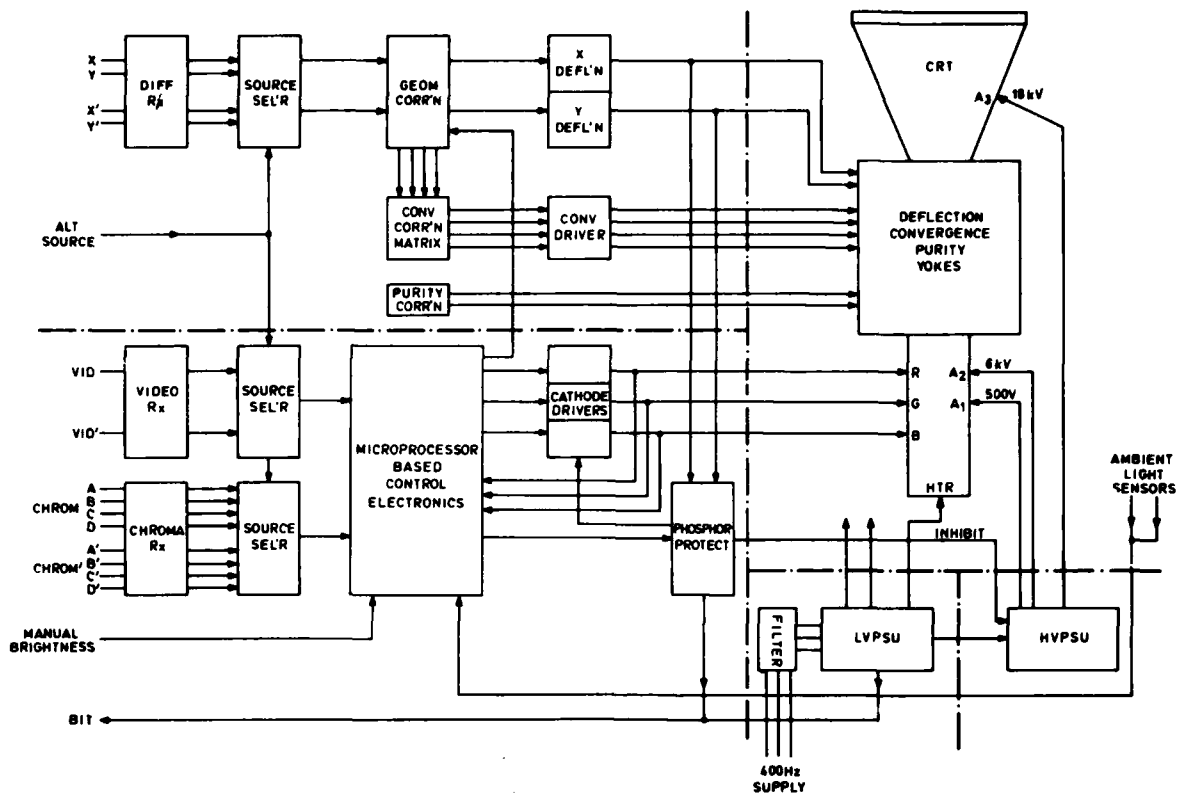


FIG. 6 DISPLAY UNIT BLOCK DIAGRAM

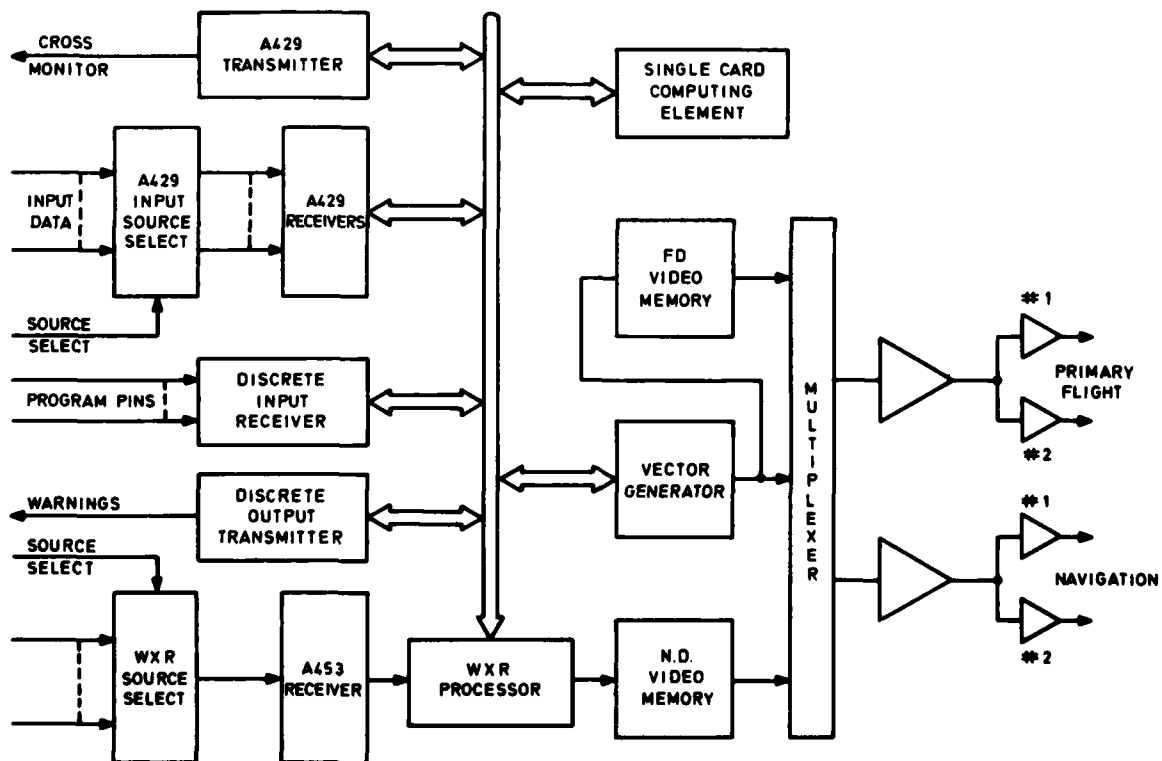


FIG. 7 SYMBOL GENERATOR BLOCK DIAGRAM

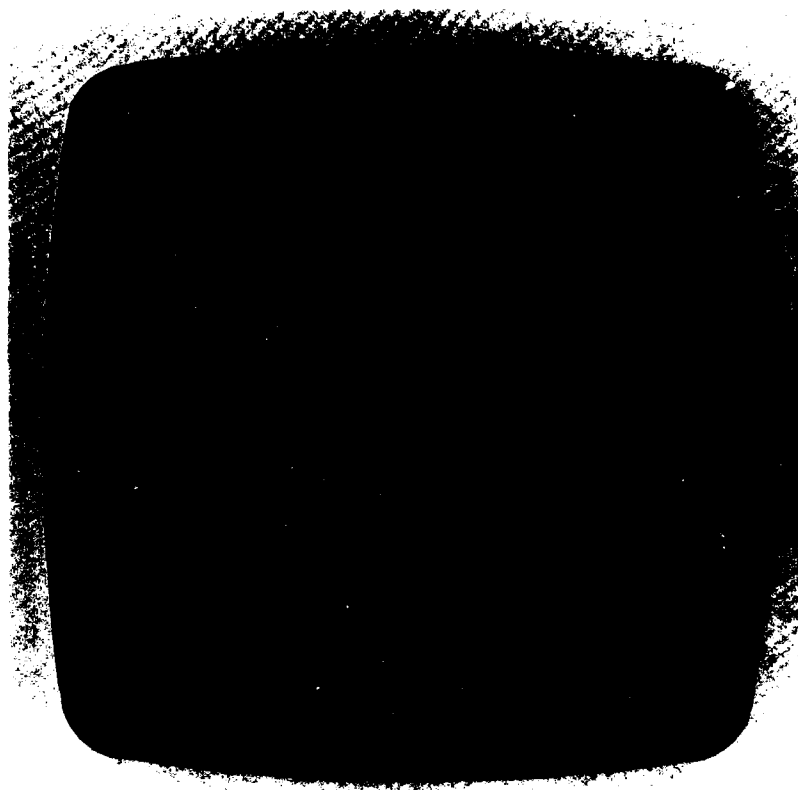


FIG.8 PRIMARY FLIGHT DISPLAY IN 200 MM X 200 MM CASE

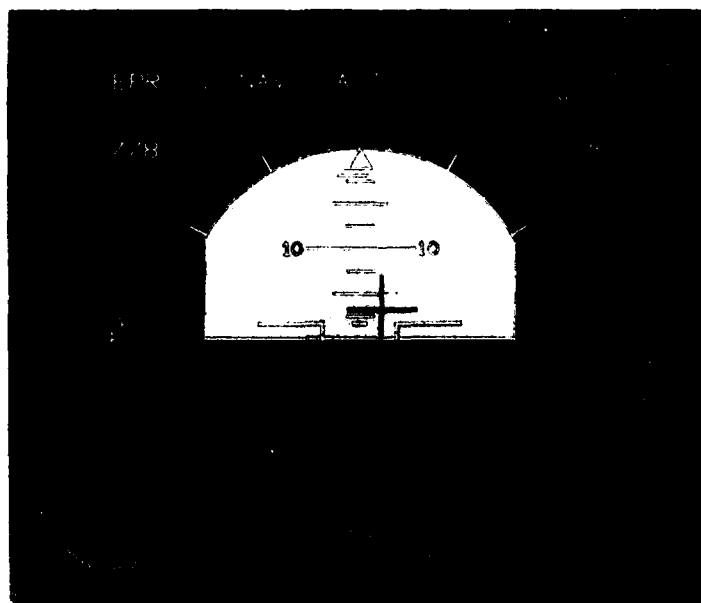


FIG.9 PRIMARY FLIGHT DISPLAY IN 180 MM X 150 MM CASE

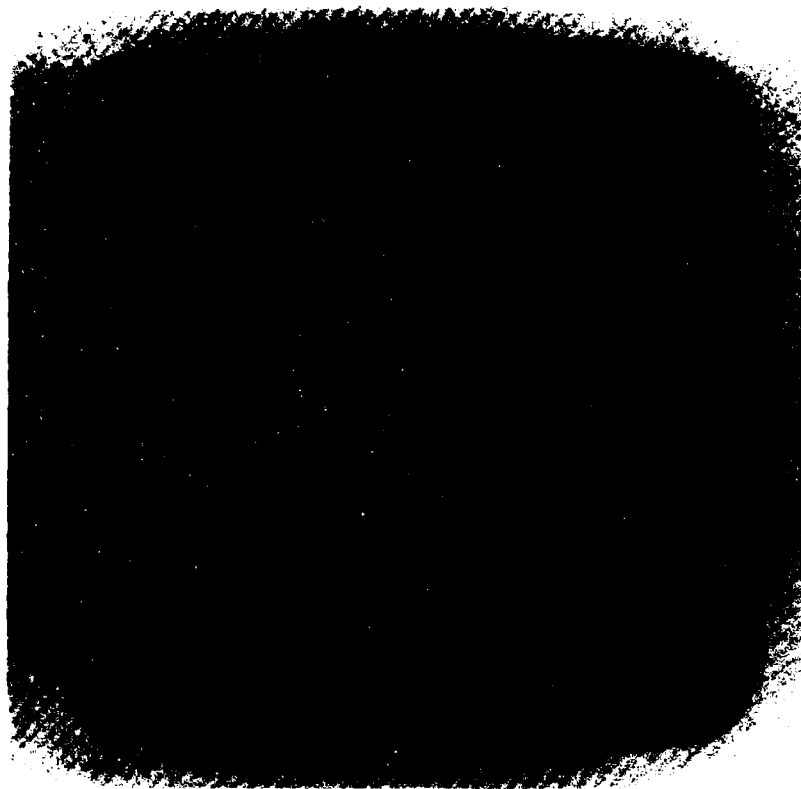


FIG.10 NAVIGATION DISPLAY IN 200 MM X 200 MM CASE

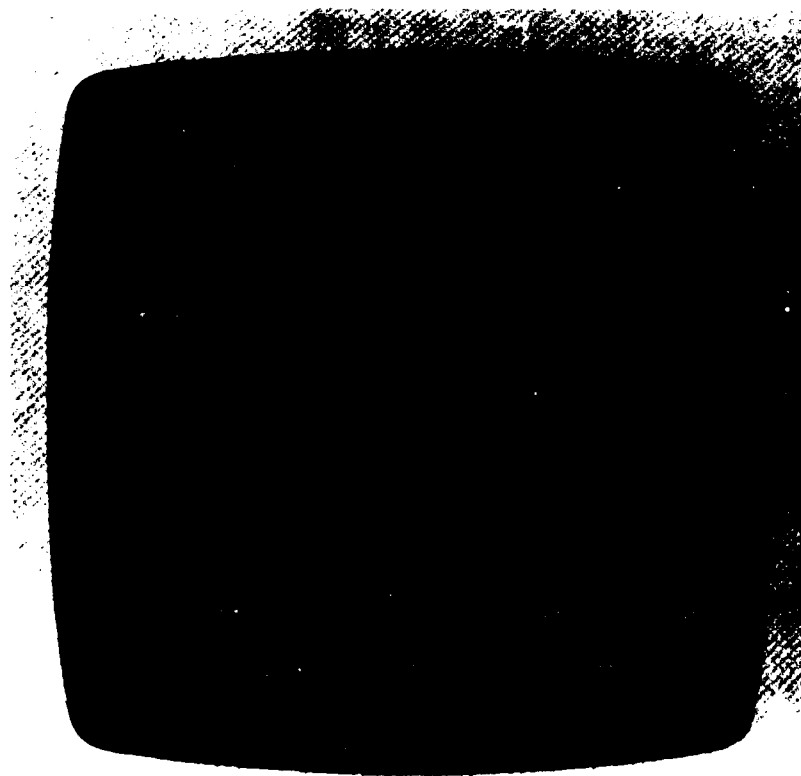


FIG.11 SYSTEMS DISPLAY IN 200 MM X 200 MM CASE

COLOR CRT DISPLAYS FOR THE COCKPIT

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SUMMARY

Color displays are currently being proposed for installation or are being installed in civilian and military aircraft cockpits. The complexity of designing a good color display is much greater than that of a monochromatic display. New human factors data and cockpit requirements need to be developed and applied to color cockpit displays so that requirements for a useable display can be generated. The color display technology needs to be evaluated with respect to satisfying the established human factors requirements. Test methodologies need to be developed to determine compliance of the color displays to the specification requirements. Finally, color displays need to be integrated into the cockpit using total cockpit human factors criteria to maximize the possible workload reduction and safety of the aircraft.

1. INTRODUCTION

Historically, cockpit Cathode Ray Tubes (CRTs) displays have had poor viewability/readability problems in high ambient cockpit light conditions. Most CRT displays had large glare shields or hoods over them to reduce the ambient light level impinging on the display surfaces. In the 1960's, an attempt was made to use CRT displays without hoods using the latest technology in CRTs and filters. These displays could be used in high ambient light but suffered from the lack of high contrast, significantly reducing the readability.

A CRT display breakthrough was achieved in the 1970's by the use of a narrow spectral emission phosphor P-43 and a matched narrow bandpass filter tuned the frequency of the P-43 emission. The first production application of the P-43 phosphor and narrow bandpass filter was an Air Force fighter aircraft and subsequently used in other Air Force and Navy fighter/attack aircraft heads-down displays. Contrast ratios of 5.6:1 as a minimum are easily achieved in a high ambient environment of 10,000 ft. candles (108,000 lux). With this level of contrast ratio available, symbology is very easily read and understood quickly. Also, an adequate number of shades of gray are available for radar and video presentations.

Much work on color CRT displays for military aircraft has been done by Thompson-CSF of Paris, France, who licensed Jet Electronics in the United States in the early 1970's to build or sell their color displays. Around 1970, a Thompson-CSF color display was demonstrated to the Air Force, however, the brightness level and contrast was totally inadequate for high ambient illumination.

The first serious Air Force activity at Aeronautical Systems Division was the preparation of a white paper in March 1978 on color CRT displays for use on cargo aircraft weather radar updates for Warner Robins AFB, Georgia. Based upon human factors testing by the Navy and the problems of viewability in sunlight, color displays were not recommended at that time.

One year after the white paper was written, a study was conducted to determine if color technology had progressed far enough to use a color CRT in a fighter aircraft environment. Simulation studies for tactical presentations indicated that a color display was highly desirable and almost necessary if most of the information was to be useful. An investigation of the industry indicated that a beam penetration color CRT with a directive filter showed the only low risk promise of using a color CRT in a military cockpit. This display was designed by Thompson-CSF and licensed by Bendix for production and sale in the United States.

In the meantime, Boeing Aircraft Corporation decided that color CRT displays would be used in the new commercial aircraft, and that for the United States industry, triggered the explosion in color display activity. In addition, the European Airbus is now available with color CRT displays. The unique part of those commercial displays is that they use a high resolution shadow mask technology. As a result of all the color display activity another investigation was made of color technology developments since the last report: specifically; can a high resolution shadow mask color CRT meet the military fighter environmental requirements?

2. HUMAN FACTORS OF COLOR DISPLAYS

In order to determine if a color display can be used in an aircraft cockpit, we first have to determine what the man-machine interface requirements are. This report attempts to establish the human factor requirements for the color display. Once these requirements are established, we can then proceed to develop the display requirements including the environmental as well as the human factor.

2.1 COLOR VISION

The color vision sensation can be defined in terms of its three perceptual attributes; lightness (apparent brightness of the visual energy for that color), Hue (visual effect from the mixing of primary components of colors, tint, shade), and

saturation (vividness of hue, purity of color). In order for a color display to be useful, it has to create a color sensation that can be perceived by the human eye. Therefore, the display must have adequate brightness, and produce a color with enough saturation under all ambient lighting conditions that maintains a significantly discernable color sensation. Defining the requirements to achieve a significantly discernable color, sensation is one of the problems with the current available human factors data for airborne cockpit environments as will be seen later.

Numerous factors affect the human eye perception of color.

- a. LUMINANCE. The sensitive elements of the eye are the rods and cones and are distributed across the retina as shown in Figure 1. Color perception varies with luminance and contrast. The eye operates in three modes depending on the luminance and wavelength of the source (Table I). These modes are the; Scotopic (rod vision, no color is perceived); Mesopic (mixed rod and cone vision, colors can be seen but much less effectively); Photopic (cone vision, total color vision). The Scotopic eye has less resolution capability and requires higher luminance modulation to make low and medium spatial frequencies visible in the display. In true Scotopic vision where the luminance is insufficient to activate the cones a second blind spot to color signals will exist in the center foveal area approximately one degrees of angle. Normal display signal levels will not be of that low of luminance to be Scotopic.
- b. WAVELENGTH. The eye varies in its response to equal radiant energy from various wavelengths according to the photopic curve for the cones and scotopic curve for the rods (Figure 2). This means photopically that if the radiant energy of red, green, and blue colors were equal, the eye would perceive that green is the brightest and red and blue significantly dimmer. The peak sensitivity of the scotopic eye is to radiant energy at 507 nm and the peak sensitivity of the photopic eye is at 555 nm. In scotopic vision, the eye does not detect color, only levels of light (white, gray, black), however, the wavelength of light determines the eyes sensitivity to this effect. The color display symbol luminance will not be low enough in most applications to reach into scotopic light levels even though the eye may be scotopically adapted. Display luminances will reach into the mesopic range. This will have an effect on color vision which will require a further separation of the color coordinates and more color saturation.
- c. ADAPTATION. The rods are very slow to adaptation to light levels compared to the cones. The adaptation time can depend upon many things such as: age, physical condition, etc. The luminance, and possibly the wavelength of the signal of the display, will have to change dependent upon the adaptation level of the eye. Data apparently doesn't exist to determine if the just noticeable differences remain the same for color determination at high ambient light levels and high display brightness levels.
- d. DURATION/FREQUENCY OF LIGHT STIMULUS. The color perception of the eye varies with the duration and frequency of the light pulses. As the pulse rate of the light changes, the misinterpretation by the eye of the luminance and wavelength will cause an apparent change in brightness and hue. Most early color human factors tests were conducted on D.C. (continuous color) sources, and may not be totally applicable to Cathode Ray Tube color technology which by its design uses pulsed light. Further discussion is provided under the subject flicker.
- e. IMAGE SIZE. The minimum image/symbol size will vary dependent upon the color of the image or symbol. Certain colors may be totally unsuitable for symbols while other colors may require a large symbol size to be seen.
- f. AMBIENT ILLUMINATION. Ambient illumination combines with the display luminance and reflectance to establish the overall eye adaptation level. The two adaptation levels of greatest concern is; the night-time 0.1 ft. candle (1.0 lux) or less and daytime direct sunlight 10,000 ft. candles (108,000 lux). At low adaptation levels the display can provide sufficient luminance, saturation and hue to accommodate the human eye characteristics except for scotopic vision. The problem arises in the high ambient illumination condition where the display is limited in providing enough color vision effects to properly discriminate the appropriate colors. The display loses contrast and the colors become desaturated, all approaching a single color point, that of white light. A display to be used in all ambient conditions requires special circuitry to adjust the colors for the full range of ambient illumination.
- g. PERIPHERAL VISION. The peripheral vision is made up primarily of rods after a couple degrees from the center of the fovea (Figure 1). The difference in hue is more difficult to detect because colors viewed peripherally appear desaturated, pale or whitish. This is due to the fact that the activity of the rods as used in scotopic vision dominates that of the cones. The brightness of color symbols may change dramatically with off-center viewing. The blues will appear much brighter because of the rod sensitivity to that wavelength (Figure 2). The reds will appear dimmer than in photopic vision and also the green colors will be significantly dimmer. The further out in the periphery the more problems occur in identifying the colors. At about 40°, only two colors appear to be perceived besides white, blue at the

shorter wavelengths and yellow-red at the long wavelengths. At approximately 10° , a blue symbol would appear 11 times brighter than red assuming equal brightness foveally. At 40° this difference would be 70 times, (Jo Ann S. Kinney, 1979). To use peripheral color vision requires symbols to be larger and their duration of presentation longer, otherwise they will appear to be white or gray. In normal aircraft cockpit applications the display will not be viewed with a fixed eye position, but will be of a roving scan-path. This will cause colors and apparent luminance to change as he views them first foveally then peripherally.

h. EYE ABNORMALITIES.

- 1) Color blindness is the inability to partially or totally distinguish certain colors.
- 2) Chromo-Stereopsis is the perception that certain colors are in front of or behind the display surface. The eye is unable to refract all wavelengths equally, short wavelengths will be focused in front of the retina when the eye is accommodated to primarily yellow and long wavelengths focused behind the retina. The eye can adapt by refocusing on another color which can cause eye fatigue if it is constantly switching. The resolution capability of the color that is out of focus is degraded until that color is refocused. The constant refocusing will cause eye fatigue and may also send a distance cue to the brain. In a symbolic display this distance effect may be more apparent creating a three dimensional display. Some people are more susceptible to this phenomenon than others with estimates being one-third the population.
- 3) Tritanopia is a rare visual defect resulting in the inability to distinguish the color blue.
- 4) Small field tritanopia is the visual defect which results in the inability to distinguish small blue colored symbols. This defect increases in numbers affected as the age of the subjects increase, (R. Merrifield, 1981).

2.2 COLOR USAGE.

Color usage in visual displays can be broken down into three methodologies. (Warren H. Teichner, 1979).

2.2.1 The addition of color provides pictorial realism and a visually pleasant experience. Color increases the esthetic appeal of the display. The aircraft operators prefer the use of color displays. The evidence from human factor test literature indicates that the pilots felt they did better with a esthetically pleasing color display, however, their performance did not significantly improve statistically.

2.2.2 Color could be used to overcome the effects of image/scene degradation due to clutter or visual noise. Color is used in this case in an attempt to enhance the image resolving and target detection process. Previous human factor studies indicate that brightness contrast is maximum for color targets when the target and surround wavelength are the same. Thus, color would not be of any help when contrast between targets and surrounds are high. Studies have also shown that the effects of color (chromatic) contrast does not contribute to the spatial resolution of images unless the brightness contrast between target and surround is very small. I do not believe enough testing has been done in this area to establish a definite position, pro or con, for this application of color. As an example of this application, look at the growth of color weather radar displays. Some applications in this category are similar to color coding applications.

2.2.3 The third use of color is in the coding of information in the display. For this purpose, color is used to represent meaning in the same way that letters, numerals or shapes might be used. Color in this case is applied to symbology and not for image resolution and detection. The appropriate use of color coding can lead to substantial performance improvements. The display designer has to understand the operators task and how the information will be used. The designer's task becomes more important as the complexity of the operators workload and density on the display increases. The designer has a variety of coding devices available to him: shape, alphanumerics, brightness/contrast levels, frequency of display (flashing), size and color. The appropriate use of these coding devices can reduce the operators workload. The inappropriate use of color coding can increase the workload and cause confusion throughout the cockpit.

- a. Color coding of information can be effective when used as follows, (M.J. Krebs and J.D. Wolf, 1979).

- 1) As an aid in locating a specific symbol on a cluttered or high density display. The workload reduction advantage is proportional to the number of symbols displayed. As the number of symbols is increased, color becomes an increasingly important cue.
- 2) As an attention getting or alerting signal to warn or inform the crew member that a change has taken place. Color coding can provide performance gains when used as a cue to alert the operator or a change in status. Caution in selecting colors for the cockpit needs to be applied and will be further detailed under color coding principles/guidelines.

- 3) As a technique for grouping similar items or separating items. The color code used for grouping needs to be relevant to the crew members task, i.e., all enemy airborne threats coded one color, and all airborne friendly aircraft another.
 - 4) As a means of increasing symbol visibility by adding the dimension of color contrast. Such would be the case if green flight control symbology was superimposed on a non-green monochromatic background or sensor imagery.
- b. Improper use of color coding can cause distracting effects which increase pilot workload and greatly reduce performance. Some examples of distracting effects are as follows (M.J. Krebs and J.D. Wolf, 1979):
- 1) The coloring of symbols whether or not that color has a task-related meaning, can cause distracting effects.
 - 2) Symbols of the same color will cause operator grouping of symbols which may be unrelated to task he is required to perform.
 - 3) Indiscriminate and unwise use of color on one display will interfere with the attention getting properties of another display or panel in the cockpit.
- c. In order to properly apply the use of color to cockpit displays, some principles and/or guidelines need to be followed, (M.J. Krebs, J.D. Wolf, and Warren H. Teichner, 1979).
- 1) When the crew members workload is very easy and the display uncluttered, color will not provide a significant performance improvement.
 - 2) If the workload is high and the task complex, color coding has to be related to the task at hand, otherwise it will degrade performance by serving as a distractor.
 - 3) Attensity is the attention-getting quality of a signal.
 - (a) The greater the difference between the symbol and other symbols or background, the greater the attensity. Thus, the greater differences in brightnesses or color separation, the greater the attensity of the symbol. The greater the shape differences between symbols, the more attensity they have. If other symbols have the same brightness, color or shape, the attensity for all of them decreases.
 - (b) The greater the novelty or surprise value of a signal, the greater the attensity. That is, the lower the probability of signal occurrence, the greater the attensity.
 - (c) Habituation to a signal decreases its attensity value. The more frequently the signal occurs without consequence, the less novelty and therefore, lessens its attensity. Attensity has critical design implications. Important or low probability visual events should "stand out" in the sense of unusual or very different color or brightness, or movement. All possible efforts should be made to minimize habituation to the event.
 - 4) The greater the number of unique values or items which can be identified along a dimension (i.e., colors, numbers, etc.) the larger the amount and greater the flexibility of coding possible. Although many colors are possible, the use of color for information coding should be restricted to a small color set. The greater the number of colors used, the more difficult it becomes for an operator to make a decision about the color of a given symbol.
 - (a) Use as few colors as possible.
 - (b) Avoid the temptation to use additional colors where the addition cannot be related to operator requirements.
 - (c) The current literature suggests that no more than 5 colors be used on operational displays.
 - 5) The greater the amount of information contained in a code, the longer the processing time required per code element. The amount of information depends upon both the number of possible codes or elements in a code set and their probabilities of occurrence.

- 6) As the rate of information transmitted along a channel to a human receiver increases, the rate of correct reception increases to a limiting value. This is associated with pilot workload and the cockpit automation/integration. When the input rate increases past that limiting value, one of the following happens:
 - (a) The rate of reception remains constant at the limiting rate resulting in varied kinds of errors of omission.
 - (b) The human establishes priorities which result in a selective reception of data and consequently selective errors of omission.
 - (c) He attempts to keep-up with the increase resulting in errors of commission as well as of omission.
- 7) Although humans can identify on an absolute basis only about 3 bits of information along a physical dimension or 4-5 bits along an arbitrary dimension such as the alphabet, they are able to process large quantities of information if allowed to organize it into discrete organizational units or chunks. The proper use of color will allow the operator to process large quantities of information through chunking.
- 8) In a display of colored shapes in which a target is defined as a green triangle and it is the only triangle and the only occurrence of green, the green and triangle are completely redundant. In the cockpit the occurrence of only one symbol shape with only one color for each is not probable, therefore, complete and total redundancy is not possible. If a variety of colors were present, but they varied independently so that they did not correlate with the target definition or shape, color would be totally non-redundant and totally irrelevant. Irrelevancy associated with total non-redundancy also impedes performance. In this case the irrelevant features act as distractors taking longer to process.
- 9) An information processing priority is taken depending on the code set and how that set is applied to the cockpit. The code set of alphanumerics, shape, brightness/contrast, frequency of display (flashing), size and color will be prioritized as to which is processed first by the human. The quoted highest priority processing is said to be language, however, I wonder if a flashing red signal would be processed first and then the shape or name processed in a cockpit situation.
- 10) The greater the temporal (time) difference between two signals in a display, the greater the probability that their temporal order will be discriminated.
- 11) Color signals cannot be expected to significantly improve performance if its principle angle of viewing is in the peripheral vision especially beyond 30° to 40°.

2.3 FLICKER.

Flicker is a fluttering or pulsating sensation caused by rapid picture or symbol brightness changes which tend to come on and off because of the stroke writing refresh rate or the field/frame interlace rates. To eliminate flicker as perceived by the human eye, numerous factors need to be taken into account in the design of the display.

- a. The visual system is not continuous in its mode of operation, stimulus intensity being denoted not by an amplitude modulation in the nervous system, but by a frequency modulation. There is, however, no carrier frequency so the result is a pulse rate modulation system, (R.J. Corps and J. Laycock, 1979). The luminance of a display image or symbol may be described not only in terms of the average luminance over time, but also in terms of the peak luminance, its duration, its rise and decay times and duration between successive peak luminance. Each of these factors affects the temporal modulation function of the visual system, (J. Laycock and R.A. Chorly, 1980).
- b. The human visual system susceptibility to flicker also varies with the adaptation level of the eye which is affected by both the ambient and the emitted display luminance. The higher emitted display luminance, the more susceptible the eye is to flicker.
- c. The flicker the eye perceives also is affected by the retinal area stimulated by the display. (Factors involving viewing distance, display size and luminance intensity.)

- d. Persistence of vision is the sensation resulting from a visual stimulus which does not disappear simultaneously with the removal of the stimulus. The sensation persists briefly after the removal of the stimulus and then gradually disappears similar to phosphor decay. I would think this factor has a direct affect on the Critical Fusion Frequency for a given display test conditions as the human subjects are varied.
- e. Some other factors affecting the eye's perception of flicker are:
 - 1) Foveal-Cortex characteristics
 - 2) Chromatic-Spherical aberration effects
 - 3) Individual age, sex, alpha rhythm characteristics
- f. The display hardware designer has to take into account many hardware factors as well as human factors in designing the display. These hardware factors need to be adjusted for the amount of information to be displayed, writing rate, data update rate, ambient illumination and scanning method (interlaced, non-interlaced raster and/or stroke written). Some of the hardware factors that need to be defined with human factors consideration in mind are:
 - 1) The display refresh rate is one of the primary parameters used to eliminate the presence of flicker on the face of the display. The refresh rate needs to be above the Critical Fusion Frequency for the given phosphor in a particular display design and application. The Critical Fusion Frequency is that display refresh rate or cycle which produces a flicker free display and results in the fusion of the light pulses as perceived by the human eye producing a smooth even brightness of the symbol or image.
 - 2) The phosphor persistence directly affects the Critical Fusion Frequency (CFF) and consequently the required refresh rate of the display. The shorter the persistence of the Cathode Ray Tube phosphor, the higher the CFF and resulting refresh rate. Phosphor persistence is generally defined in terms of the time in seconds for the phosphor brightness to decay to 10% of the original peak luminance.
 - 3) The luminance of the display directly affects the CFF and refresh rate of the display. The higher the luminance of the display, the higher the CFF and required refresh rate of the display for foveal viewing. Flicker is perceived in the peripheral portion of the retina more readily at low illumination levels and less readily at higher illumination levels. Foveal vision is less susceptible to flicker detection at low illumination levels than at higher illumination levels, (Semple, Heapy, Conway and Burnette, 1971). The design engineer needs to consider both peripheral night vision and daytime foveal vision when selecting the display refresh rate to maintain CFF.

Much of the flicker experimentation and test data has been conducted at low illumination levels in a laboratory environment. Additional test data is required on high illumination levels such as used in the fighter cockpit. The use of multiple CRT displays in an integrated cockpit or side-by-side two-man cockpit needs to be investigated for flicker effects. Flicker effects could be generated by: different luminance wavelengths on color displays; non-synchronization of the refresh rate for the various displays; varying rate of data update; or possibly sequential updating of the display due to multiplex bus timing.

3.0 COLOR CATHODE RAY TUBE DISPLAY DESIGN REQUIREMENTS RESULTING FROM CURRENT HUMAN FACTORS DATA.

COLOR DISPLAY HARDWARE REQUIREMENTS.

The color CRT human factor test data for high ambient cockpit environments is almost non-existent. Boeing Aircraft Commercial Division of Seattle, Washington, is currently conducting human factors testing. Thompson-CSF of Paris, France, has conducted human factors tests to verify hypothesis and equations they developed in specifying a beam penetration three color CRT display. The Air Force has requested its laboratories to investigate color display requirements as pertains to the fighter cockpit environment and to establish criteria to be used in evaluating hardware.

The problem, however, is that the Air Force is proceeding to install or accept programs which include color CRT displays in the cockpit. The current situation requires specification requirements which are in many cases best guesses based on experience, past test data extrapolated to a cockpit environment and current human factors test programs.

The Air Force cannot wait for years while the human factors test data and display criteria is being developed so we must proceed with what knowledge is available now and update our requirements as our knowledge increases. Some or all of the following color display hardware requirements may be applied to hardware specifications.

- a. **BRIGHTNESS.** The display brightness capability needs to be specified for the total range of operating conditions. The minimum level of brightness required for both stroke symbology and peak line brightness in the highest shade of gray for a video raster, as seen at the pilot's eye, needs to be specified for day and night conditions. The minimum daytime brightness specified in the past for monochromatic displays has been a minimum of 200 ft. lamberts (686 cd/m^2). This is required to achieve enough dynamic range when combined with the contrast ratio requirement to use 6 shades of gray for the video raster in 10,000 ft. candles (108,000 lux) ambient illumination. The minimum daytime level of brightness for monochromatic stroke symbology only display, has been specified as 100 ft. lamberts (343 cd/m^2). If stroke symbology is overlaid on the raster, then the minimum symbology brightness has to be above the peak white of the raster. This level is required to assure that the pilot can readily see the symbology when combined with the contrast ratio requirement in a 10,000 ft. candle (108,000 lux) ambient illumination. This minimum 100 ft. lambert level of brightness is also required because of the adaptation level of the eye to 10,000 ft. candle (108,000 lux) bright surround by either looking at bright clouds or being in bright clouds in a bubble canopy. When the eye has stopped down its iris to accommodate to the high ambient and the eye has adapted to the bright surround, a minimum level of symbol luminance is required to stimulate the eye. The exact brightness level is not certain and needs to be defined under rigorous testing techniques. The Air Force is using 100 ft. candles (343 cd/m^2) because of one of our human factor laboratory recommendations and the success that number has achieved in the field.

The brightness at nighttime needs to be continuously adjustable for both the video raster and symbology down to a level of 0.07 ft. lamberts (0.24 cd/m^2). This requirement was established during cockpit lighting testing on conventional instruments when they are used on terrain following night flights. Another aspect of brightness that is more relevant at night time is the uniformity of brightness of the display. If the brightness of symbols or parts of symbols are allowed to vary significantly invalid data will be presented by either symbol dropout or segment dropout. The uniformity of brightness is generally specified in the range of ± 10 to 15% of the average brightness of a given brightness symbol set or within a symbol. This minimizes invalid symbology due to dropout because of the adaptation level of the eye.

The brightness requirements need to be specified with the designed writing speed and refresh rate of the display. The brightness measurement needs to be made with a slit aperture in an accurate photometer using a photopic curve and an integrating time which simulates the human eye. Measurements need to be made with all display filters shields and coatings in place to determine the brightness levels the pilot's eye will see. The minimum and maximum symbol line width needs to be specified because this affects the brightness of the display with the narrow high energy line measuring brighter, however, appearing to the eye as less bright than a broader line of the same brightness.

The problem with establishing brightness requirements for color displays is that narrow bandpass filters with the efficiency of the monochromatic filter are not available. This results in an increased requirement in brightness to maintain a given contrast ratio. It also increases the brightness level of the colors to reduce the high ambient illumination tendency to desaturate the colors.

The brightness of the reds and blues will appear much less in any color CRT display because of the eye efficiency at those wavelengths (Fig.3) For a given condition of high voltage, electron beam current and similar phosphor efficiencies, the green will be perceived and measured at a much higher brightness level with a photometer even though the radiant energy may be equivalent. It would therefore seem logical that the color green be used in all symbology and especially in video sensor displays that do not need color to produce a pronounced performance improvement. With the current state-of-the-art, a full color raster in a bubble canopy fighter cockpit is not feasible. The use of a directive filter will reduce the effects of high ambient illumination on the full color raster but not totally solve the high ambient problem. However, the directive filters could cause moiré patterns when applied to shadow mask CRT if not properly designed. One way around the high ambient raster problem is to provide a color raster up to the point where the display is becoming judgemental or taking a longer time to interpret and then switch it to an all green video raster either automatically or manually.

The color CRT display can be very effective when used in the stroke writing mode even in high ambient illumination. The apparent brightness equality between the colors can be more easily achieved by adjusting the writing speed and beam current of the colors. Adequate color brightness can be achieved because the writing speed of the electron beam for a given current density directly affects the symbol

brightness in the stroke mode. The electron beam writing speed is much less than in the raster mode resulting in a significantly brighter display.

The brightness measurement technique of a shadow mask color CRT versus the beam penetration color CRT can result in significantly different values of brightness. This difference depending upon the size of the photometer aperture. A very small aperture can measure inside the shadow mask phosphor dot which can result in brightness levels of a 1000 ft. lambert or more (Fig.4). To achieve an average luminance value, the phosphor area divided by the overall phosphor triad area needs to be multiplied by the peak phosphor dot luminance. The average luminance value depends on the shadow mask design and is approximately 13-15% of peak phosphor dot luminance. A method which uses a larger area measurement such as the slit aperture can also be used on both display types as long as a number of shadow mask phosphor dots are included in the slit area. The method of measurement will have to be standardized.

The high peak intensity of the shadow mask dots may stimulate the eye more than what is implied by the calculated average area luminance. I have not found human factor data to verify or disprove this theory. If the shadow mask brightness is actually perceived by the eye as brighter than would be obtained with an area measurement, then a "K" factor is required when comparing shadow mask and beam penetration CRTs.

The current recommended color brightnesses for a stroke written fighter cockpit display as measured with a photopic photometer should be a minimum of 100 ft. lamberts (343 cd/m²) of area brightness. If the stroke symbology is over-laying the raster, then the brightness needs to be 40% greater as a minimum than the peak of the raster if the symbol is the same color as the raster. This requirement may change if the human factor data establishes a new minimum brightness with high ambient surround.

The current recommended color brightness for a raster written fighter cockpit display as measured with a photopic photometer should be a minimum of 200 ft. lamberts (686 cd/m²) of area brightness. It is recognized that this requirement cannot be met by a color display for all colors, however, I do not feel that the quality of the display has to suffer just to say we are using a color display. This requirement is necessary to detect the color contrasts and hue changes in a complex color image. When a color display is used as a multi-purpose display presenting stroke, raster and/or stroke and raster, the raster portion of the display could be presented in the high efficiency green which can meet this requirement. If the video raster presentation is color coded such as used in weather radar where three colors are used and the colors are digitally transitioned from one color to the next, then it would be satisfactory to specify the same brightness conditions as used for stroke symbology.

The brightness uniformity of the color displays should be $\pm 15\%$ of the average brightness for that color and symbol set or raster shade of gray color.

It should be noted that the brightness values required under this paragraph may be greatly exceeded in order to achieve other requirements such as contrast, chrominance difference, etc. These requirements are the minimum in case a breakthrough is achieved in color contrast enhancement.

- b. **CONTRAST.** Contrast is defined as the ratio of brightness (luminance) when comparing one symbol brightness to another symbol or background brightness. The contrast ratio is defined for CRT displays as:

$$\text{Contrast Ratio} - \text{C.R.} = \frac{B_S}{B_B}$$

where B_S = average brightness of symbol.

B_B = average brightness of background 1/8 inch (3 mm) away from symbol or average brightness of dimmer symbol or shade of gray.

The contrast ratio of purely stroke monochromatic symbolic CRT displays are specified to have a minimum contrast ratio (CR) of 4.0:1 when measured in a 10,000 ft. candle (108,000 lux) ambient illumination. Stroke symbology when overlaying a raster presentation requires a minimum C.R. of 1.4 over the brightest shade of raster with a C.R. of 2.0:1 preferred.

The contrast ratio of a monochromatic raster display is specified as having a C.R. of 5.6:1 for peak video in a 10,000 ft. candle (108,000 lux) ambient illumination. That's for displays requiring a minimum of 6 shades of gray with 1.4:1 ($\sqrt{2}$) contrast ratio steps between each shade of gray. The background or zero video level is considered the

first shade of gray.

The contrast ratio determines how well the display will be seen. The recognition and readability criteria for a cockpit should require that 95% of the population recognizes what is displayed 100% of the time. Time is also a critical factor because the pilot in high workload conditions can only spend 2-3 seconds viewing a display. Therefore, the contrast ratio selected should assure that a display can be quickly read and interpreted. It is fully recognized that humans can detect brightness differences in a range of 2% to 8% (1.02 to 1.08 contrast ratio), however, that human factor data is not applicable to a cockpit situation where life and death decisions need to be made in split-seconds.

The recommended color display contrast ratio for stroke written color symbology is 2.0:1 when measured in a 10,000 ft. candle (108,000 lux) ambient illumination. The reduced contrast ratio when compared to a monochromatic requirement is due to two reasons; (1) color will be used for coding instead of two brightness levels and, (2) the technology of filters will not easily permit higher levels of C.R. unless directive filters are used. The chrominance difference and/or color discrimination index requirement also have to be met.

The recommended color display contrast ratio for a raster display can be divided into three parts; (1) the contrast ratio of 5.6:1 for an all green raster display is the same as for the monochromatic conditions. The all green raster will provide the required dynamic range for video or sensor imagery; (2) the contrast ratio for a color coded raster should be the same as stroke symbology 2.0:1 as measured in a 10,000 ft. candle (108,000 lux) ambient illumination. The chrominance difference and/or color discrimination index requirements also have to be met. It is felt that if the video is color coded to provide digital levels of color, such as in a weather radar, then the contrast requirement for each color could be lower than for one color as long as the colors remained separable and not desaturated under high ambient conditions; (3) the contrast ratio for a complex color image where many brightness levels and hues are used to generate a real world picture cannot be defined by the Air Force at this time. Additional human factor data and display evaluation is required. I do not believe a complex real world color image will be available in the high ambient bubble canopy fighter cockpit without hoods or very directive filters in the near future. Color graphics with distinct color brightnesses and color cutoffs as used in color coding can be used in the cockpit to generate pictorial images approaching near real world imagery.

c. CHROMATICITY (CHROMINANCE) DIFFERENCE AND COLOR DIFFERENCE.

In order to use color displays the operator has to be able to distinguish between the various colors under all operating ambient illumination and vibration conditions. The high ambient illumination causes a desaturation of the color to a point where colors can become indistinguishable from each other. Proper filtering, adequate brightness and contrast will assure of adequate separation of colors. Figures 5 and 6 show the effects of how the color coordinates change when a high ambient illuminance condition is created on a display with a neutral density filter and one with a directive filter. As can be seen in the one case where the directive filter is used, the color remains separated and can be easily distinguished. In the case of shadow mask tubes vibration can cause a symbol color change. The display susceptibility to vibration will determine how much color change will occur for a given vibration input.

Currently there are three methods of defining colors; the CIE (International Commission on Illumination) 1931, X and Y diagram; the CIE 1960, UCS (Uniform Color Space), u and v diagram and the most recent CIE 1976, UCS u and v' diagram (Fig. 7 and 8). The CIE-UCS diagrams were an attempt to create a color space in which the distance between any two color points is intended to represent a measure of the perceived difference between the corresponding colors. The CIE-1960 UCS caused McAdams color ellipses to appear more round. The CIE-1976 UCS is an attempt to extend the v' axis to make most of the color ellipses more round.

Two current methods are being used to measure color displays. The photometer using tristimulus filters from which X and Y, u and v and the u and v' coordinates can be calculated. The second and preferred method is the spectroradiometer where the display is scanned for radiant energy versus wavelength which measures the spectral power of the display. An algorithm in the computer, plots out the 1931 CIE, CIE 1960 UCS or CIE 1976 UCS diagram and prints the X and Y, u and v or they u and v' coordinates of each color. The equations for tristimulus colorimetry are as follows:

X = Tristimulus Red Y = Tristimulus Green Z = Tristimulus Blue

1) CIE 1931 x and y Diagram Coordinates

$$x = \frac{X}{X+Y+Z} \quad y = \frac{Y}{X+Y+Z}$$

2) CIE 1960 UCS u and v Diagram Coordinates

$$u = \frac{4x}{-2x+12y+3} \quad v = \frac{6y}{-2x+12y+3}$$

3) CIE 1976 UCS u and v' Diagram Coordinates

$$u = \frac{4x}{-2x+12y+3} \quad v' = \frac{9y}{-2x+12y+3}$$

One of the methods of assuring that the difference between colors remain adequate for comfortable viewing and definition is to establish a criteria for chrominance difference between colors. Chrominance difference is the vector distance on the two dimension UCS diagram between two color points. Chrominance distance (CD) = $[(u_1 - u_2)^2 + (v_1 - v_2)^2]^{\frac{1}{2}}$.

Galves and Brun in 1975 indicated that the smallest discernable chrominance difference detectable by the eye to be 0.00384 of chrominance difference. Their physiological laboratory tests showed that for easy and comfortable detection the chrominance difference must be 7 times the smallest discernable level resulting in a C.D. = 0.027. Their tests were conducted on a three color display beam penetration CRT and may not be directly applicable to 6 or 7 color shadow mask display. When more colors are added, new test data must be developed for the new condition because more colors can add confusion which affected the 100% identification criteria and reduces a given color range of movement in the UCS diagram. Blue colors which were not tested may need a larger chrominance difference because of the human factors problems with blue symbols.

Another method for self-luminous displays of assuring that the difference between colors remain an adequate distance away from each other is a criteria which uses color difference. Color difference is defined as the vector distance between two color points on a three dimensional diagram.

$$\text{Color difference C.D.E.} = (L_1 - L_2)^2 + (u_1 - u_2)^2 + (v_1 - v_2)^2^{\frac{1}{2}}$$

L is proportional to luminance (Field 1978)

The color difference vector takes into account the luminance differences in the two colors. However, the units of measure on luminance proportionality to "L" was not defined. I have not found human factor test data that establishes minimum color differences using the CDE equation. Additional human factors testing needs to be done to use this equation and establish minimum cockpit criteria.

The recommended requirement for maintaining color separation in the display, based on current literature knowledge, is to specify as follows. The minimum chrominance difference (CD) between any two colors shall be 0.27 for zero ambient illumination and 0.027 under 10,000 ft. candles (108,000 lux) ambient illumination using the CIE 1960 UCS system.

$$CD = [(u_1 - u_2)^2 + (v_1 - v_2)^2]^{\frac{1}{2}}$$

Based on limited testing of a display that we evaluated which is easily viewable and the colors easily distinguishable, a more conservative chrominance difference recommendation in high ambient would be a CD of .060. We did not determine the lowest CD, just a CD of a display that is easy to use in high ambient.

Hopefully, human factor test data will be able to verify which equation is more applicable, CD or CDE. Also, what a high workload cockpit CD requirement should be for all colors. In Figure 9, a diagram is used for development testing and explanation purposes that makes chrominance and color differences more easily understood (R. Merrifield, 1981). Testing is also required to determine if the values used for CD using the CIE 1960 UCS is applicable to a CD using the CIE 1976 UCS.

d. DISCRIMINATION INDEX, DETECTION INDEX AND EFFECTIVE DETECTION INDEX.

Galves and Brun in 1975 developed a set of equations which can be used as detection index on monochromatic displays and as a discrimination index when differentiating between two signals having different colors

and luminance. This equation was based on testing conducted on a beam penetration CRT with two primary colors and a third combination color yellow. The applicability of this equation and criteria established is in doubt when applying it to a display which has three primary colors and four cockpit useable combination colors. The applicability of this equation and criteria when using the CIE 1976 UCS coordinates needs to be reverified. The equation does provide the luminance proportions and/or factors which were not available in the CDE (color difference) equation. Numerous equations are available in the Optical Society of America Journal which attempts to use luminance in the color difference equation, however, no single method has been decided upon. To expedite the writing of a color display requirement, it has been decided that the Galves and Brun equation will be used at this time. Additional human factor testing should be conducted at the earliest possible time to determine if the criteria and equation developed can be applied to the whole spectrum of colors and whether or not it should become the Air Force standard equation set.

$$\text{Discrimination Index} - \text{DI} = \left[\frac{\text{CD}}{.027}^2 + \frac{\log \text{CR}}{.15}^2 \right]^{1/2}$$

(Detection Index)

Some literature and specifications require a DI equal to 1 for all ambient conditions between symbols and background and between symbols of different colors or luminance values. This then assumes that for the same wavelength color, contrast ratios of 1.4:1 are satisfactory for cockpit applications. As can be seen from the contrast ratio paragraph for a monochrome display a CR of 4.0:1 was recommended and for color display a CR of 2.0:1. A DI equal to one also assumes that for the same brightness colors that a chrominance difference of .027 is satisfactory. A conservative recommendation was a CD = 0.060.

Some applications of the equations assume a standard D65 white as a point to compare all colors against. If this is done, then all the colors on a multicolor display are compared to the white and not to each other. The criteria for color cockpit CRTs has to be one color against another as well as against the background developed by the high ambient source.

The recommended Discrimination Index at this current time for aircraft cockpit applications is a DI = 2. This DI applies to all ambient lighting conditions and is, between symbols and background, between symbols of different colors and/or luminance values, and between different luminance values of the same color symbols. This area needs to be tested further to establish human factor criteria for a DI value for all colors. CIE Publication No. 19 (1972) indicates that to achieve a visibility level defined in the publication, a DI of 7 is required. The DI of 2 recommended does not take into account all cockpit factors.

The Galves and Brun Effective Detection Index (EDI) equation is the Detection/Discrimination Index weighted to take into account two physiological factors:

- 1) Sensitivity of the eye to contrast as a function of the display brightness. The sensitivity to contrast is less when viewing a display having a background luminance below 2915 ft. lamberts (10,000 cd/m²). See Figure 10, Relative Contrast Sensitivity (RCS).
- 2) A Transient Adaptation Factor takes into account the changes in the eye as a function of the ratio of the ambient surround luminance and the display luminance. When the display operator has been looking at bright clouds or his display is just below the glare shield, his eye has adjusted to the high ambient surround. When the display is read, his sensitivity to the display luminance is decreased. In some cases, a time is required for the eye to adapt when the bright surround is out of the eye's view, such as a display low in the cockpit. In other cases, the bright surround is in view of the eye and the adaptation to the display luminance never achieved because of the bright surround bias. See Figure 11, Transient Adaptation Factor (TAF).

$$\text{EDI} = \text{DI} \times \text{RCS} \times \text{TAF}$$

The Effective Detection Index takes into account the display brightness and the display installation in the aircraft with its ambient lighting conditions. Galves and Brun recommended that an EDI greater or equal to 0.6 be used to permit comfortable detection and identification under any ambient lighting. If a display meets the minimum requirements of 100 ft. lamberts (343 cd/m²) and the fighter cockpit bright surround is 10,000 ft. candles (108,000 lux) then the RCS = 0.8 and the TAF = 0.1. In order to meet an EDI of 0.6 with a RCS = 0.8 and a TAF = 0.1, then the DI needs to be 7.5. Further testing by the Air Force will attempt to verify the requirements and curves used on the

EDI. For the present this appears to be the best approach known.

e. FLICKER.

Flicker was described in Section 2.3. There are basically three display modes which require flicker considerations.

- 1) STROKE/CALIGRAPHIC DISPLAY. The stroke display generally writes the symbols in order for a given display format using direct electron beam control. The symbol set is written "x" times a second called the refresh rate of the display. The refresh rate has been specified as 50 Hz for Head-Up Displays and P-43 phosphor Head-Down Displays. Testing of color displays has indicated that the P-22 phosphor has a shorter persistence and that flicker can be perceived at 50 Hz refresh rate. Some specifications are requiring a refresh rate of 80 Hz to assure that peripheral vision is not also affected. In any event the recommended refresh rate for stroke written shadow mask tubes using a P-22 type phosphor needs to be 60 Hz or greater. Beam penetration color CRTs may be a lower refresh rate dependent upon the phosphor types used and a human factors peripheral test verification.
- 2) VIDEO RASTER. The video raster in the U.S. is a 1/60 of a second field rate and 1/30 of a second frame rate commonly called 30/60 frame/field rate. Two fields create one frame for the 2:1 interlace. One-half of the display is updated every 1/60 of a second writing every other line. With the high brightness levels used in CRT monochromatic and on future color displays, the 30/60 frame/field rate may be too low especially when the displays are viewed peripherally. The visual system is capable of detecting flicker at frequencies as great as 80 Hz at these conditions.

Studies by a U.S. company indicate that in a side-by-side cockpit the frame/field rate on color displays had to be increased to 40/80 to reduce the flicker problems encountered. It is also known that symbols if not properly sized so that an uneven number of lines are used, flicker can appear foveally up to 50/100 frame/field rates.

Recommendations for avoiding or minimizing the effects of flicker on raster displays is as follows:

- (a) On raster displays that are only symbolic in nature and not displaying sensor video, the frame/field rates should be a minimum of 40/80. On displays that use symbols with an odd line count on the horizontal symbol lines, the frame/field rate should be 50/100 minimum.
- (b) Recommend that sensor and weapon video on military systems be developed with a frame/field rate of 40/80. In the meantime, current 30/60 frame/field rate systems have to be used and will require a master sync system. (See Master Sync Discussion).
- 3) VIDEO RASTER WITH STROKE SYMBOLOGY. This particular case is called the hybrid mode where sensor video is first written and then between each field on the flyback the stroke symbology is written. The frame/field rate is as recommended, however, the stroke symbology refresh rate should be 60 or 80 depending on the field rate required for the system.

MASTER SYNC SYSTEM. With multiple CRTs in the cockpit and each system supplying its own sync, a perceived flicker can be generated by the apparent differences in refresh rates, frame/field rates and/or their sync timing. This flicker would be more easily perceived in the peripheral vision.

Without proper design the unintentional flicker generated by multiple CRT displays will lessen the attentiveness of the intentionally flashed symbols for alerting purposes. If the flicker reaches a 8 to 15 Hz frequency, it will cause confusion, loss of operator performance and in some individuals loss of consciousness (Laycock and Chorley, 1980).

It is recommended that all cockpits using multiple CRT displays whether monochromatic and/or color provide for a master timing and/or sync system to drive the display. The system should be adequately redundant and fail safe so that failure of the system will not cause the loss of the displays.

4.0 COLOR DISPLAY TECHNOLOGIES.

It is not the intent of this paper to provide a detailed review with all the pro's and con's of each color display technology. A brief description of the two leading color display technologies, beam penetration and shadow mask designs, will be provided. The third technology that appears to have renewed interest in the industry is the beam index color tube, however, additional development is required to make it a major contender for the airborne market.

4.1 BEAM PENETRATION COLOR CRT.

The beam penetration color CRT is basically a monochromatic tube with a special phosphor deposition. The phosphor screen technologies are varied such as a mixed phosphor screen, an onion skin phosphor screen, and a layered phosphor screen. In all cases the green phosphor is protected by a barrier layer so that a certain energy level beam is required to penetrate it. The primary phosphor colors are red and green. By the use of a switching high voltage power supply, the beam energy can be varied to produce colors lying on a line between the primary phosphor CIE 1976 UCS coordinates. Generally three colors are provided; red at the lowest voltage 9-10 KV, yellow at an intermediate voltage 13-16 KV and green at a high voltage 18-20 KV. The red is a saturated red, however, the green is not pure because of the red phosphor emission. The brightness of the red is lower than the yellow which is lower than the green at the same writing rate. In order to have a more uniform brightness for the three colors, the writing speed of each color needs to be different.

The beam penetration color CRT is as rugged as a monochromatic CRT. The critical display component of a color display using this CRT is the high voltage switching power supply. Beam penetration color displays are being proposed for fighter cockpits where three colors are required and an inherently rugged design is also required.

The display average stroke symbol brightness can be higher than a shadow mask tube because the beam current can be twice that used in a shadow mask tube, and the black matrix/shadow mask does not reduce the average brightness to 15% of that possible. The contrast, however, may suffer because 85-95% of the ambient reaching the phosphor of a beam penetration tube is reflected versus 15-20% of a black matrix shadow mask CRT. One thing is certain, the stroke written display is readily viewable in 10,000 ft. candles (108,000 lux) when the light source is out of the viewing angle cone of a directive filter. The monochromatic video raster is significantly dimmer and would not be totally useable in the fighter cockpit suffering from the lack of dynamic range. A two or three color raster is out of the question for cockpits, however, it may be used in a non-cockpit area of the aircraft where ambient light is severely limited. As more and more symbology is put on larger displays, the brightness decreases to a point where the color requirements cannot be met.

4.2 SHADOW MASK COLOR CRT.

The shadow mask color CRT is used in the commercial television market. There are four current shadow mask designs popularly used as shown in Figure 12. The Sony Trinitron is currently being used in commercial and military cockpit displays for weather radar systems. The delta gun and in-line gun with round hole designs are the current popular technology being used in most proposed high resolution, high brightness and high vibration environment color CRT display applications. Three phosphor colors are used; green, red and blue, which when plotted out on the CIE 1976 UCS diagram produce three points of a triangle (Fig. 13). It is theoretically possible to generate any color in that triangle area by the proper combination of the three color phosphors. Although many colors and hues are possible, the display should be limited to no more than eight; white, black, green, red, blue, cyan, yellow and magenta.

The shadow mask CRT has been redesigned by the Japanese into a small display such as a 5 inch by 5 inch CRT and have greatly improved the resolution of the phosphor dot pattern to approximately 84 triad dots per inch. However, the use of a small display with this shadow mask CRT creates a video raster system that is display limited. The display is perfectly satisfactory for stroke type symbology, however, the 5 inch by 5 inch is limited to approximately 400 lines resolution in the horizontal and vertical direction. To display a 525 video raster with good horizontal resolution, you need to increase the resolution of the triad dots to 110 per inch or increase the size of the display to 7 inch by 7 inch while maintaining 84 triad dots per inch. The use of a 875 video raster on a shadow mask color CRT is not currently possible without severely limiting the resolution of the video sensor system.

The most critical environmental consideration for the shadow mask color CRTs has been vibration and shock. If the shadow mask changes position, the symbol color changes, and if the mask tears, it could cause a loss of the display or symbols. Vibration testing has been witnessed at 3.0 g's RMS random vibration in one direction with no display change at a couple of facilities. Random vibration tests at 5.7 g's RMS in one direction produced multi-colored symbols but readable at one facility and no change at another facility. Since then a test at 9 g's RMS random vibration has been conducted with no permanent changes occurring. It is apparent that short-term random vibration levels as seen in the cockpit will not have a detrimental effect on the shadow mask color CRT especially if the tube is properly mounted in the display. The problem of concern now is the effects of long term vibration or shock on the shadow mask which could cause failure of the mask due to fatigue. Additional testing needs to be conducted on all designs to determine long-term vibration effects at the earliest possible time. The larger shadow mask CRTs such as a 7 inch by 7 inch tube will be more sensitive to vibration. The Sony Trinitron and slotted masks are also more sensitive to vibration.

The shadow mask tube requires good convergence for cockpit application. In order to generate colors which are a combination of two or more phosphor colors, the guns have to be aligned on the same symbol line position. If the guns are not lined up, the symbol is made up of two colors. One side of the symbol line one color, and the other side another color. Vibration can also affect convergence especially if the gun alignments are not properly ruggedized.

The brightness of a shadow mask color CRT is very satisfactory in high ambient 10,000 ft. candles (108,000 lux) ambient when the symbology is stroke written. In order to achieve equal symbol brightness, the colors have to be written at different stroke speeds. Raster brightness is not adequate for use in a bubble canopy cockpit. The use of a directive filter can allow the use of the raster display into higher ambient illumination, but not the 10,000 ft. candles (108,000 lux) ambient surround. The color raster brightness is much greater than that achievable by the beam penetration CRT. The black matrix surround of the phosphor dots reduces the reflectance of the ambient to a level of 15-20% thus providing an improvement in contrast of the display.

5.0 APPLICATIONS OF COLOR CRTs TO THE COCKPIT.

Obviously for aesthetic reasons, all displays in the cockpit could be color, however, one has to look at the limitations of the displays and the cockpit requirements before deciding on integrating color displays into the cockpit.

a. GENERAL REQUIREMENT.

One general requirement that may have an impact on which color technology will be selected is that of the use of yellow and red in the crew station. The use of yellow is reserved for caution and the use of red is reserved for warning. In order to retain the attentivity (attention getting properties) of yellow and red, we must develop standard ground rules for color displays. The first ground rule is that the use of yellow is reserved for cautions, unknown (potential threats), approaching limit exceedances, approachment to heavy storm cells, etc. The second ground rule is that the use of red is reserved for warnings, fire, threats, limit exceedance, storm cells, etc.

The application of these ground rules has to be made in the light of the human factors data known about attentivity. For example, if we generate an engine display with a yellow and red area on the engine scales for caution (temporary limit exceedance) and warning (never exceed limit) the pilot will be viewing yellow and red symbology constantly, thus reducing the attentivity value of these colors. It would be much better and more attention getting if the scale was totally green with a green shape coding for both the yellow and red area. Thus, when the parameter value has reached the appropriate shape code area, the total scale would turn yellow and then subsequently would turn totally red if the red shape code area was entered. A possible alternative would be to turn the total scale yellow except for the red shape code area would be red and then switch to all red when that area is entered. The third ground rule requires that the use of yellow or red will be avoided in symbology and displays until the actual condition exists.

It should be noted that not all color CRT displays can generate some of the standard required aviation red, yellow and green colors. Aviation color standards should be revised to reflect the new technology. If these ground rules are followed, then the beam penetration CRT will only have a green format for normal operation unless it is used as a caution and warning display or a tactical display in a hostile environment.

b. SENSOR DISPLAYS.

The use of a color CRT display is not recommended as the primary sensor display. If the maximum resolution of the best sensor on the aircraft or projected for the aircraft is less than 400 resolution elements horizontally or vertically, then a color display may be considered. An example of this case would be a weather radar.

The Air Force does not provide a full color sensor on military aircraft and therefore the requirement for a full color raster sensor display does not exist at this time. Digitized color coding can be used to enhance sensor presentation, however, not much work has been done in developing this capability or human factors testing to justify its usefulness.

The color display in the raster mode is not capable of adequate brightness and contrast ratio to use in the maximum ambient lighting condition. A directive filter will improve its performance, but not to the point of a monochromatic display.

To meet the resolution requirements of a 525 video raster, a 7 inch square color shadow mask CRT with 84 triad dots per inch would be required. Development work is being conducted on such a large color display. The use of a color shadow mask display for 875 video raster systems is not possible at this time without seriously degrading the system performance. These recommendations are made based upon a viewing distance of 28 inches and a visual acuity of 1 min. of arc.

The recommended primary sensor display is a monochromatic P-43 phosphor CRT with a narrow bandpass filter with a minimum size of 5 inches square with 7 inches preferred. The higher the resolution of the display, the larger the display should be. A Weapon System Operator may require two sensor displays which are monochromatic. A color shadow mask display can be used as a backup to the primary monochromatic sensor display for use in degraded modes of operation.

c. TACTICAL AND MAP DISPLAYS.

The tactical presentation which shows the horizontal plan form is greatly enhanced when color is added to the display. Color coding of symbology allows the operators performance to significantly improve when moderate to high density presentations are used through the principle of chunking. All threats in red, all unknowns in yellow, and all friendly forces in green is one method of color coding that allows chunking of data. Many studies have shown that operator performance improves significantly when color is used in ground and airborne tactical displays. The displays have to be stroke written in order to be used in high ambient cockpit conditions. In this particular application, a beam penetration CRT can be used unless other color chunking is necessary.

A map presentation is also a horizontal plan form and current paper maps and projected maps are in full color. Remote map readers have been developed which provide for the use of a standard display in the cockpit and a raster presentation of the map on that display. A monochromatic map presentation does not convey as much information as a full color map presentation seen on a shadow mask color CRT. The use of a shadow mask color CRT with a suitably designed directive filter can be used for full color raster presentations of video from a remote map reader. The color raster may not be seen in full cockpit high ambient illumination, however, the display could be switched to a monochromatic high brightness green presentation under those conditions.

The use of a color beam penetration or shadow mask color CRT can be used for stick map or stroke written electronic map presentations. The display can provide performance improvements through the use of color. Human factors testing and level of detail investigations are currently in progress.

d. FLIGHT CONTROL AND ENGINE DISPLAYS.

Performance improvements through the use of color in the presentation of flight control and engine data have not been found in the human factors testing conducted so far. This would tend to indicate that all symbology could be the same color and a monochromatic display should be used. However, there are situations that occur in the flight control and engine data presentations that color could well serve as a performance improver as an alerting function. The example of the use of color as an alerting function in engine data is provided under sub-paragraph 5.0(a). Color in flight control symbology could alert the pilot to "g" limits, stall speeds, max. flight envelope parameters, impending unstable conditions, etc.

Many cockpit display vendors application of colors to the flight and engine instruments have not taken into account the attentivity getting value of certain colors. The indiscriminate and non-standard use of colors for symbols can destroy the benefits that color displays can bring to the cockpit.

e. HEAD-UP DISPLAYS.

Some research work is being conducted into multiple color head-up displays. The work in this area is very sketchy. The color principles for flight control data would apply to head-up displays.

6.0 CONCLUSION.

I believe the future military cockpit will have multiple CRT displays without any conventional primary or standby instruments. The architecture and design for this could be a completely separate paper but suffice it to say that the crew station would be as safe if not safer than current cockpit instrumentation. Each cockpit operator would have 3 to 4 CRT displays with pushbuttons around the periphery. At least one CRT display should be a high resolution monochromatic display for a sensor display. The other CRTs most likely will be shadow mask color CRTs. Redundant integrated control panels could be either color CRTs or flat panel displays. Color CRTs in the cockpit are the wave of the future unless something catastrophic happens to them or because of them. If the costs are the same or within 5 or 10% of monochromatic displays, the change will be all the more rapid. Not many people would trade in their color television for a black and white television, so once you have shown pilots color displays, how are you going to get them back to all monochrome displays.

Color displays can be a real benefit to the cockpit; however, we need to apply the color technology wisely to produce the greatest reward. Improper application and requirements can be detrimental to the crew station so we must proceed cautiously. We must not throw in a color display just for the sake of saying we have a color display in the cockpit. Indiscriminate and non-standard use of colors in displays can destroy the benefits

that color displays can bring to the cockpit, i.e. improved performance, reduced workload and safer operation.

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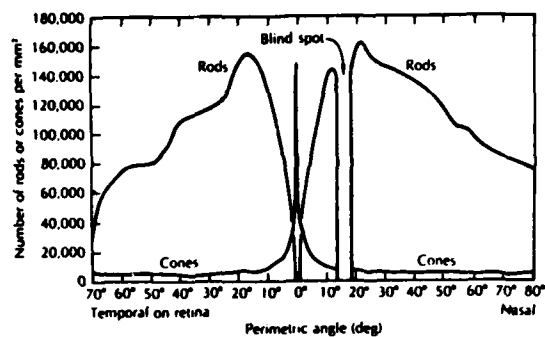


FIGURE 1
DISTRIBUTION OF RODS AND CONES THROUGH-
OUT THE RETINA (FROM PIRENNE, 1967)

BLACK MATRIX SCREEN

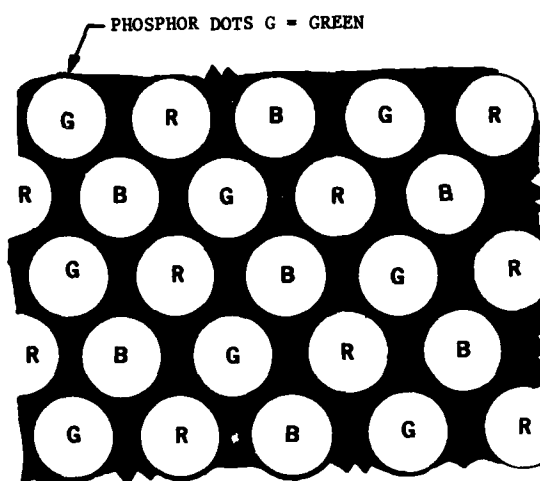


FIGURE 4
RED, GREEN & BLUE PHOSPHOR DOTS
ON BLACK MATRIX SCREEN

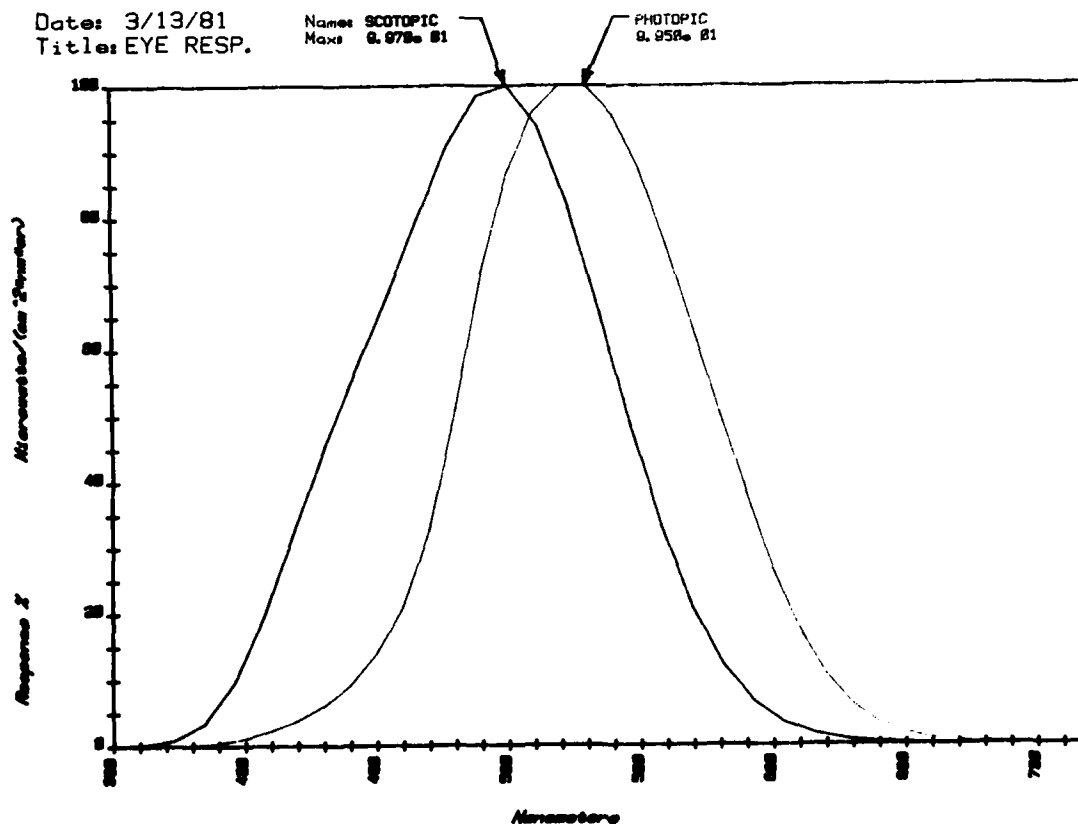


FIGURE 2
SCOTOPIC AND PHOTOPIC

FIGURE 3
PHOTOPIC

Device name ND FILTER

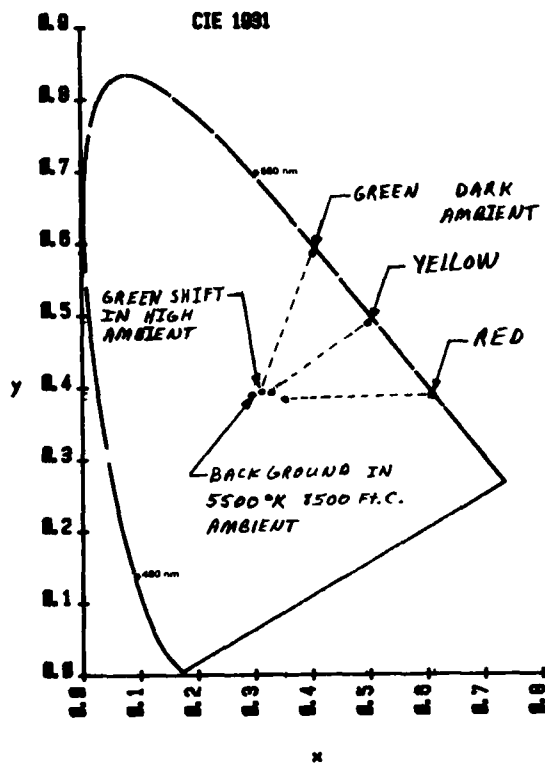


FIGURE 5

COLOR COORDINATE SHIFT WITH AMBIENT USING NEUTRAL DENSITY FILTER. POINT SOURCE OF LIGHT AT 30° TO PERPENDICULAR. BEAM PENETRATION CRT.

Device name DIRECTIVE

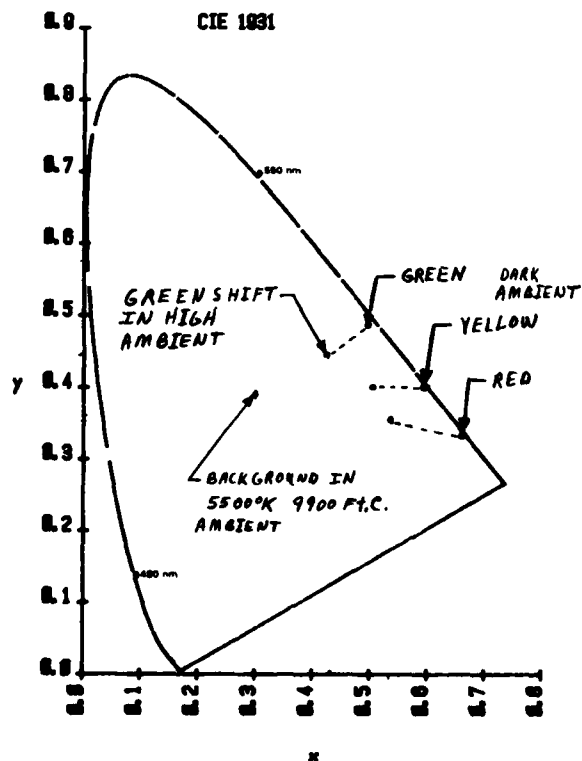


FIGURE 6

COLOR COORDINATE SHIFTS WITH AMBIENT USING DIRECTIVE FILTER. POINT SOURCE OF LIGHT OUTSIDE FILTER ACCEPTANCE CONE. BEAM PENETRATION CRT.

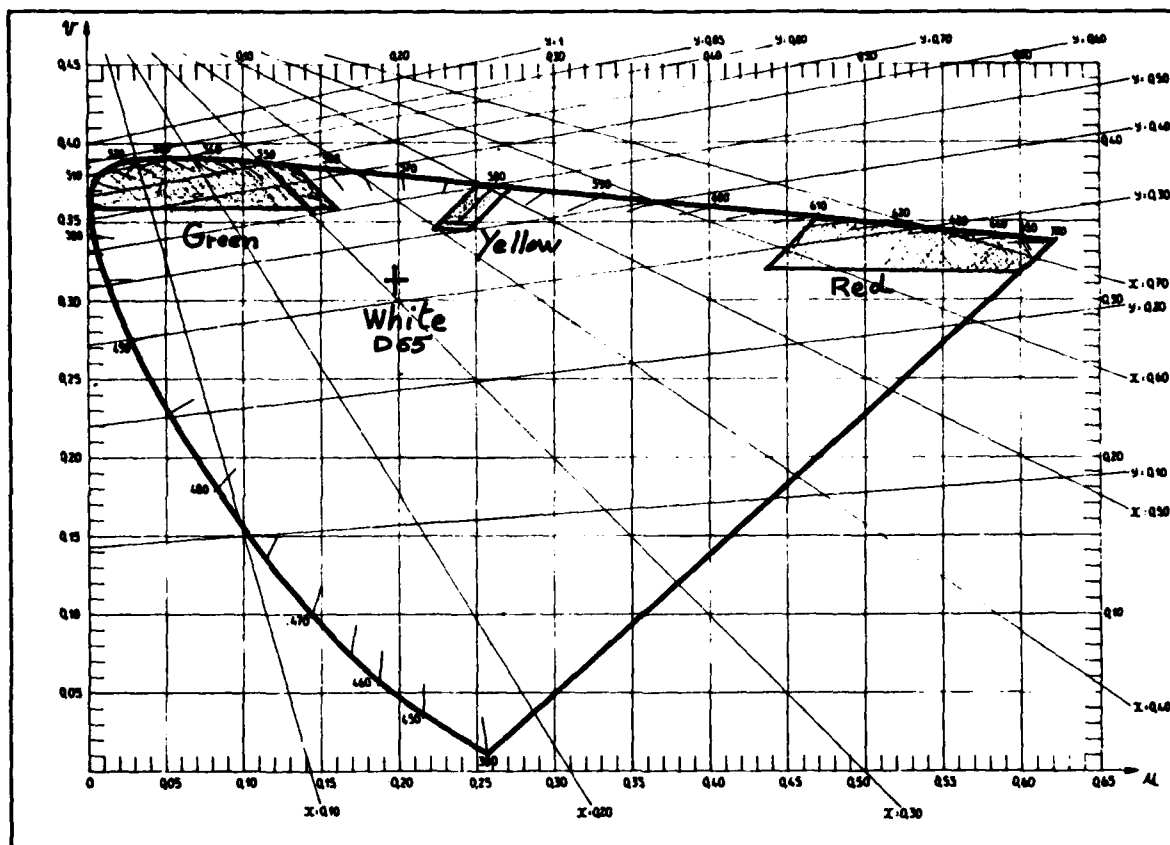


FIGURE 7
CIE 1960 UCS DIAGRAM

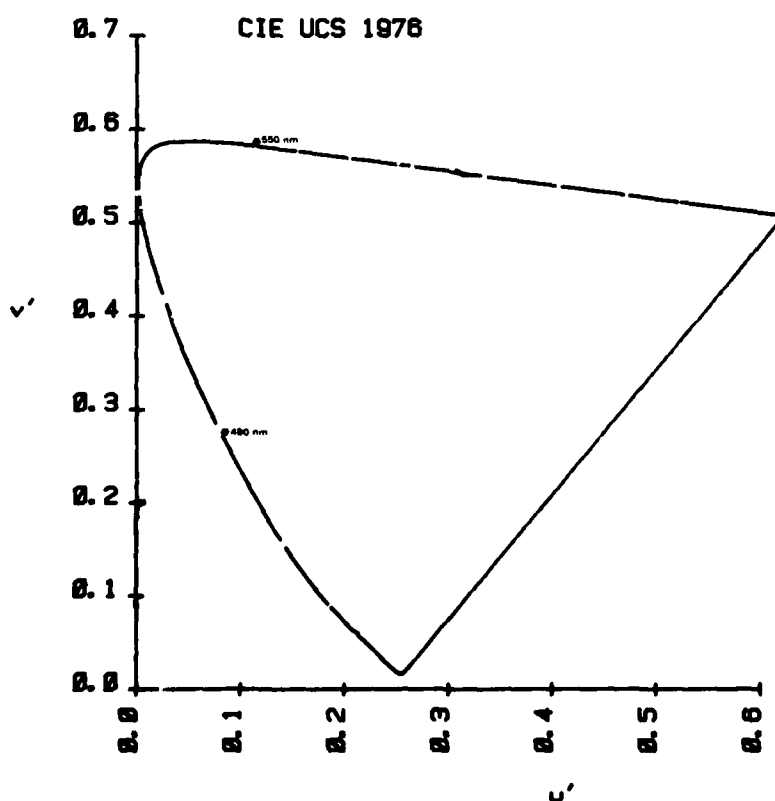


FIGURE 8
CIE 1976 UCS DIAGRAM

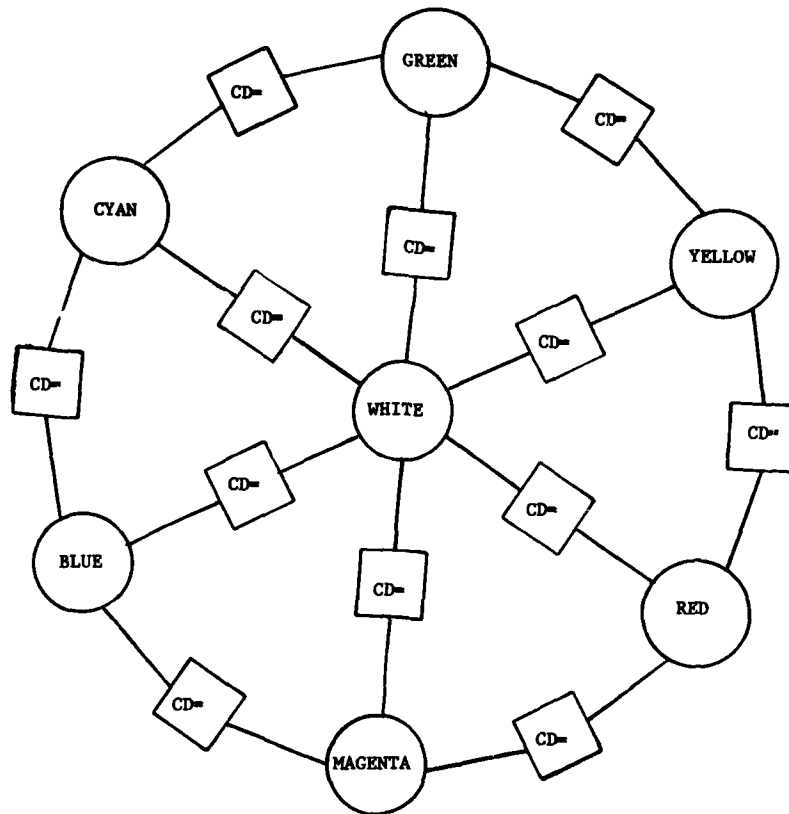


FIGURE 9

COLOR DIFFERENCES WHEEL CD, CDE, DI, OR EDI CAN BE USED IN SQUARES

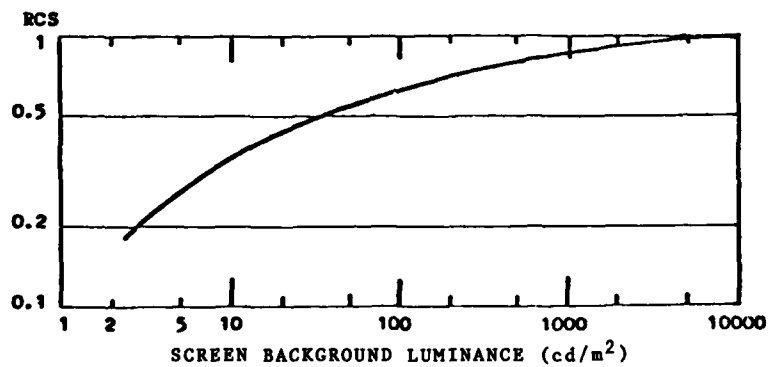


FIGURE 10

RELATIVE CONTRAST SENSITIVITY COEFFICIENT

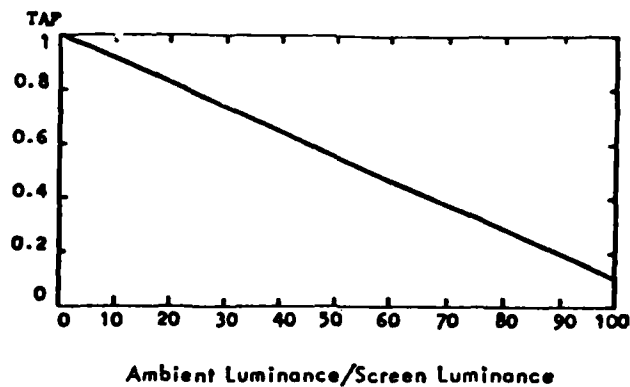


FIGURE 11

TOTAL ADAPTATION FACTOR (TAF)
VERSUS LUMINANCE RATIO

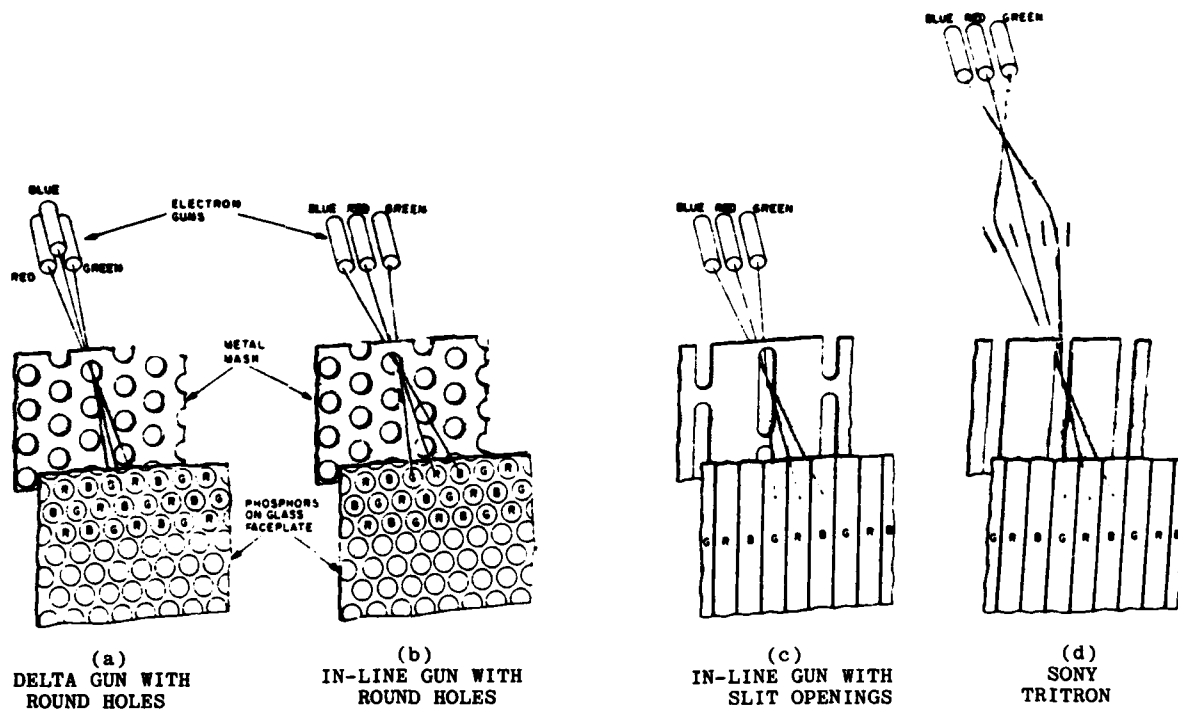
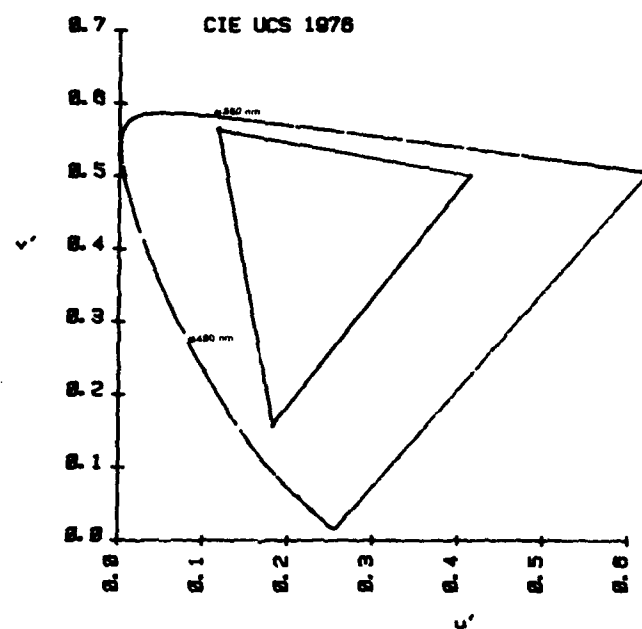


FIGURE 12
SCHEMATIC OF FOUR SHADOW MASK SYSTEMS

CONDITION	LUMINANCE in cd/m^2	LOG cd/m^2	DESCRIPTION
PHOTOPIC	100 000	5	HAZY SKY
CONE VISION	10 000	4	CLEAR SKY
COLOR VISION	1 000	3	
	100	2	ORDINARY ROOM
	10	1	ILLUMINATION COM- FORTABLE READING
MESOPIC	1	0	
MIXED	.1	-1	FULL MOON
	.01	-2	
SCOTOPIC	.001	-3	STARLIGHT
ROD VISION	.000 1	-4	
BLACK, GRAY, WHITE	.000 01	-5	ABSOLUTE THRESHOLD
VISION	.000 001	-6	

TABLE 1
TYPICAL LUMINANCE VALUES FOR ROD AND CONE VISION

Device names PHOSPHOR1



Device names PHOSPHOR2

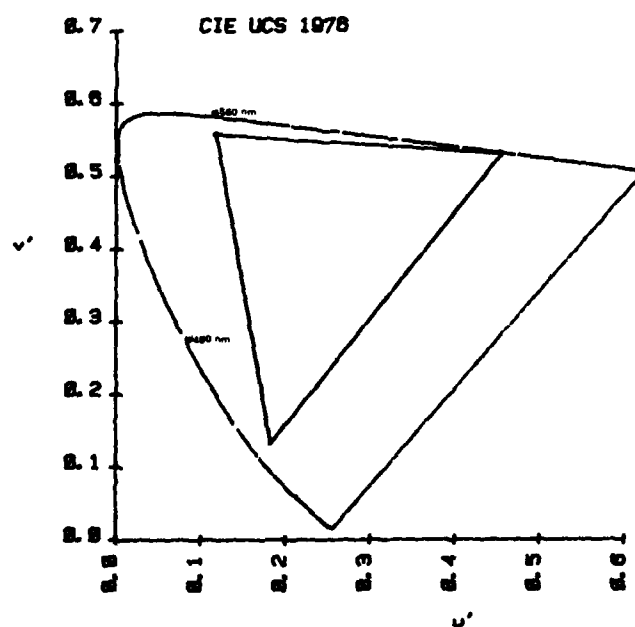


FIGURE 13

CIE 1976 UCS DIAGRAMS WITH DIFFERENT
TYPE PHOSPHOR TRIANGLES

HEAD UP DISPLAYS

by

Claude Maureau
Product Manager
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1. - GENERAL

The appellation "HEAD UP DISPLAY" (HUD) derives directly from the position of the pilot's head while he is regarding the said display. In fact it could have been possible to choose an appellation based upon a characteristic more specific to this type of display.

They could for example be called OPEN DISPLAYS to stress the point that HUDs present information to the pilots without depriving them of a SIMULTANEOUS EXTERNAL VIEW.

The human eye being what it is, this implies that the HUDs be COLLIMATED displays. They could possibly be semi collimated, but if we agree that, in our field of study, infinity begins not very far in front of the eye, it is possible to speak only about collimation. This will stress the point that HUDs may give information to the pilots with DIRECTIONAL value.

This expose does not intend to deal with all display systems problems. It intends to open discussion essentially about the two main specific HUD characteristics pointed out above.

By the way, to begin with, these two characteristics give a reply to the first question that could be put : why a HUD ? The reply comes indeed as a direct consequence of HUD characteristics : HUDs are useful for aircraft with good external view ahead, each time there is an interest to superimpose a DIRECTIONAL OPEN DISPLAY upon this EXTERNAL VIEW. This interest exists in any situation where there is something to be looked at in the vicinity of the aircraft trajectory. This means that HUD should be used by tactical aircraft pilots most of the time, and if possible, continually for low altitude flight. This means also that HUD should be used by transport aircraft pilots - at least by one of them - for any phase of flight near the ground, and especially, during take off, approach and landings.

With the support of the French administration and because of the company's experience in this domain, THOMSON-CSF entered into the study and development of HUD systems about ten years ago, for military or civilian application with fixed and mobile (helmet mounted) HUDs.

2. - HUDs ARE OPEN DISPLAYS

The open external view may be provided in at least two ways :

- . In a direct manner through the HUD combiner with superimposed symbology inside HUD/Field of View (FOV).
The HUD combiner qualities are currently specified in terms of optical transmissibility for transparency, and, by reflectivity of symbology wavelength as one of the factors of contrast. Optical transmissibility was some years ago between 50 and 70 %, but, it is presently between 70 and 80 % for refractive HUDs, and, about 90 % for holographic HUDs.
- . In an indirect manner, artificially by associating an image forming sensor with a display which has to provide a collimated video image of that which is seen through the sensor FOV.

The second manner which introduces a synthetic external view may be used in two cases :

- when the exterior view is masked by the airframe,
- when direct view through the atmosphere is hindered by aerosols in the air or by lack of external light.

One example of a "mask see through" device is the TV sight repeater system for the rear seat pilot of two seater tandem aircraft. THOMSON-CSF TMV 544 sight repeaters have been in use for a few years on board dual MIRAGE F1, and are also to be used on board dual MIRAGE 2000. They give at angular scale 1/1 a collimated synthetic forward view for the back seat pilot, with a good insertion at the center of direct external peripheral view.

Such an insertion is unfortunately more difficult when video collimated images are provided at night in a binocular HUD combiner, as what could be seen directly in scotopic perifoveal vision through and around the combiner is then lost.

Remarks

- a) It is to be noted that, if displays and control systems are generally considered as being the interface between man and machine, HUDs are a little more than that, as they include the direct or synthetic external "windshield" view as well as the display of information given by other sensors.

Going a little further in that approach, the aircraft - with its pilot inside - may then be considered from the outside as being a bird or an insect, and with such an approach, it is tempting to look for ideas for HUD improvements in the solution given by nature to problems of environmental perception. Such an approach for the study of the "systems of the nineties" could be fruitful, mostly perhaps to resolve the problems of Field of View introduced in the third chapter of this lecture.

- b) In each case it is of primary importance to remember that, ultimately, the information is to be assimilated correctly by a human brain directly associated with human eyes, and that, before going further with clever ideas of new systems it is good to check its adaptation to human physical and psychic functions.

As an elementary example, we may remember the importance of checking the consistency of Transfer Modulation Function (TMF) of image-forming subsystems with the same function between display and pilot's eye, under different illumination conditions.

- c) Indeed, it is not enough to develop a HUD well adapted to a pilot installed in stable viewing conditions, if, the cockpit arrangement - including system controls - does not allow the pilot to stay in the stable viewing condition. From that point of view we have to keep in mind that, if we may discuss as a separate subject the HUD specific characteristics, inversely, we would not define separately HUD specifications for an aircraft development - HUD being only a part of the displays and controls to be installed in a cockpit.

In an ideal display system the pilot would be able to stay head-up continually to avoid reaccommodation and readaptation to rapid changes of brightness between the interior and the exterior. For aircraft with two pilots side by side this may be obtained by task sharing, but, for single pilot aircraft this is less easy to obtain due to the relative sluggishness of human eye readaptation even if this human eye is very admirable from many other points of view and compared to the eye of other animals.

3. - HUDs ARE DIRECTIONAL DISPLAYS

- . Collimated displays provide information inside a certain FCV, first inside the limits of the HUD/total FOV (TFOV), and then, within the HUD/Instantaneous FOV (IFOV) which is a function of pilot's eye position referred to the HUD pupil.
- . The FOVs presently provided for HUD are significantly larger than those which were provided with the gunsights used during past years. For refractive HUDs the TFOV is usually about 20 to 25°, the greatest part of this IFOV being actually used by IFOV, at least in bearing. Thus, the THOMSON-CSF VE 130 of the MIRAGE 2000 provides for normal pilot eye position about 20° in bearing and 18° in elevation for the IFOV. Holographic HUDs, in development presently, offer even wider fields in bearing : between 30 and 35°.

Presently these values may still be considered as consistent with current operational needs. Indeed, except for aircraft with high nose up attitudes or very low speed, current drifts can be absorbed, and, similarly, for traditional axial weapons (guns, rockets), depression angles are easily absorbed and displayed with great accuracy.

- . Limitation of HUD/FOV has begun anyway in the last years to appear as not always satisfactory. One of the reasons has been the entry into operational use of new off-boresight weapons including air-to-air missiles with homing heads capable of target lock on at $\pm 60^\circ$ from axis (such as the new air-to-air French missiles), and for sure, in such a case a small increment of the FOV of current HUD would be meaningless.

Happily a new family of OPEN DIRECTIONAL SIGHTS/DISPLAYS has appeared :
HELMET MOUNTED SIGHTS/DISPLAYS (HMS/HMD).

Presently HMS production models are already flying with the US Navy, and, HMS/HMD developmental models of several manufacturers - including my company THOMSON-CSF are flying in many places.

Such devices allow discriminatory target designation way out of the FOV of HUDs, being thus complementary to them.

HMDs, in the following years, could also possibly give the proof that they are really the best HUD formula for helicopters. Presently some progress may remain to be made in order to adapt them to hidden reactions of human vision but perhaps part of the progress will be made through continued in-flight study of methods for pilot education.

For fixed wing combat aircraft, fixed HUDs should be retained for the execution of basic flight and fire control functions for some more years, including possibly the next generation of combat aircraft supposed to enter operational service at the beginning of the nineties. But these HUDs could be somewhat different to the present models.

The problem of FOV is to become more and more acute, not only to take into account the generalisation of the use of offboresight missiles, but also to take into account the new CCV concept which could be applied to aircraft equipped with electrically-driven control surfaces, inducing greater angles between instantaneous trajectory direction and aircraft axis.

For these types of aircraft, why not, as suggested here above, look for ideas of new solutions in some of the systems existing in the animal world, this being, either "CRUSTACEAN" mobile elementary FOV, or "DIPTEREAN" juxtaposition of several elementary FOV, or possibly a combination of both ?

.../

- . Without prejudice to the study of very high performance new formulae for the future of HUDs, to meet the needs of some unsophisticated aircraft programs - some rather cheap technical solutions have to be based upon cost effectiveness studies.

We have not here to discuss methods for cost evaluation, but for effectiveness evaluation we may say that the methods must always rely upon a reference to the end application of envisaged operations.

From that point of view effectiveness may be compared for some chosen action typical of the mission assigned to the considered aircraft.

Hereafter is an example, with the computation of the ground surfaces intercepted by the conical respective solid angles of different size of HDD/FOV considered as one of the ways to appreciate HUD operational effectiveness for low altitude flying. It shows that the same ratio - 1.23 - of increase of the useful ground surface intercepted will be obtained :

- when increasing a 20° FOV up to 24°
- and when increasing a 24° FOV up to 35°.

Even if these figures are only a part of the HUD effectiveness factor, it is not uninteresting to consider them in relation to the fact that the price to be paid for the second increment of HUD/FOV would be a lot higher than for the first one.

In any case, to get practical results it is not enough to increase HUD/TFOV, as, after HUD installation on the considered aircraft, an IFOV is also to be allowed from pilot installation in the cockpit and the importance of cockpit forward visibility.

4. - CONCLUSION

Concerning the future of the HUD concept it is possible without risk of error to affirm that HUDs will have an important future for any type of aircraft.

It is more difficult to say exactly what the future HUDs will be.
I invite your discussion on this subject.

With only two preliminary remarks :

- (1) HUDs are not to be conceived by equipment manufacturers working on their own, but rather in discussion and collaboration with aircraft manufacturers responsible for the overall cockpit design.
- (2) Modern HUDs are to be installed on board training aircraft to give an early start to the education of the pilots of future operational aircraft, civilian as well as military. This is certainly a condition for full benefit to be derived from these systems.



Figure 1

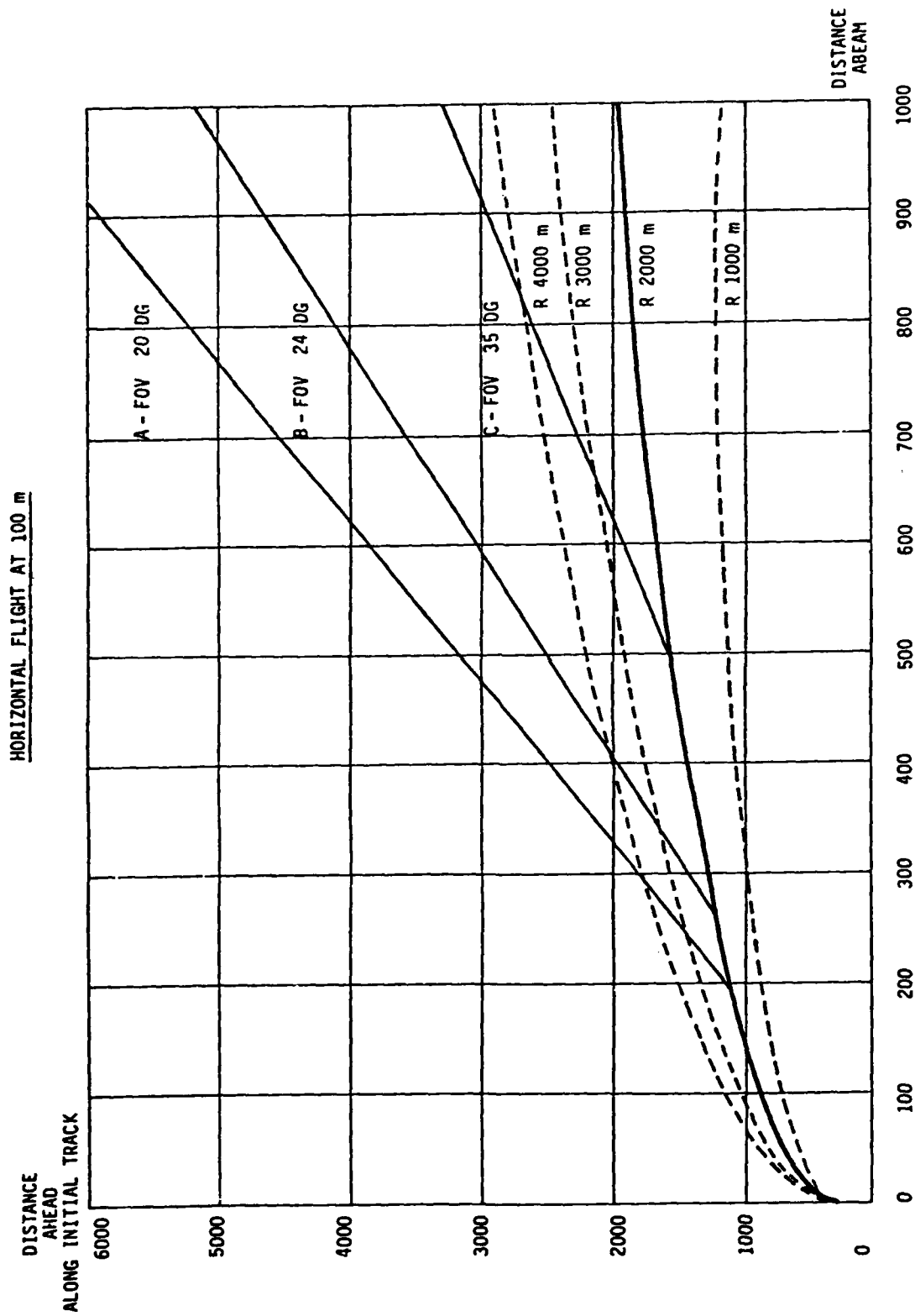


Figure 2

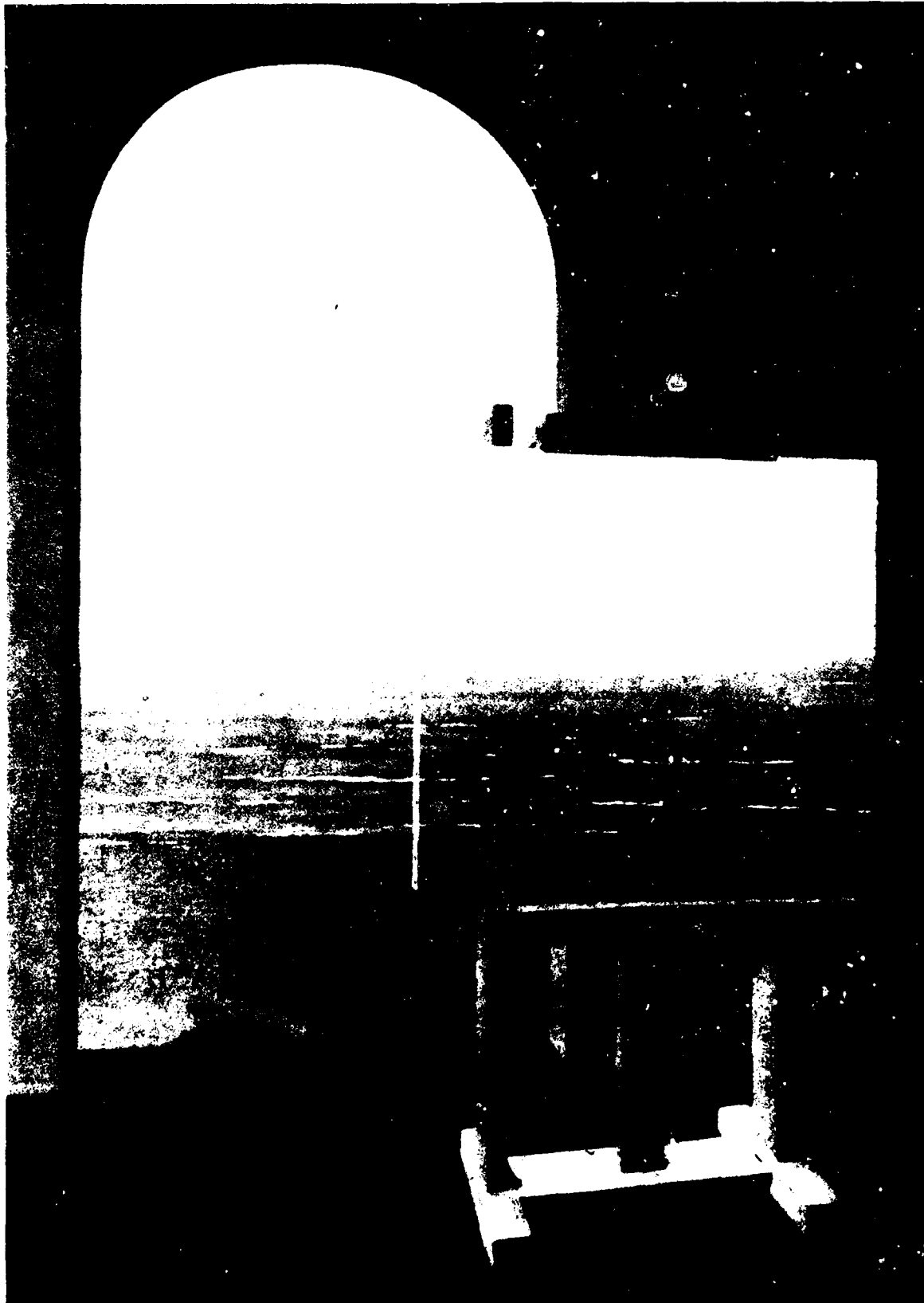


Figure 3

TMV 544 for rear seat pilot on board two seater

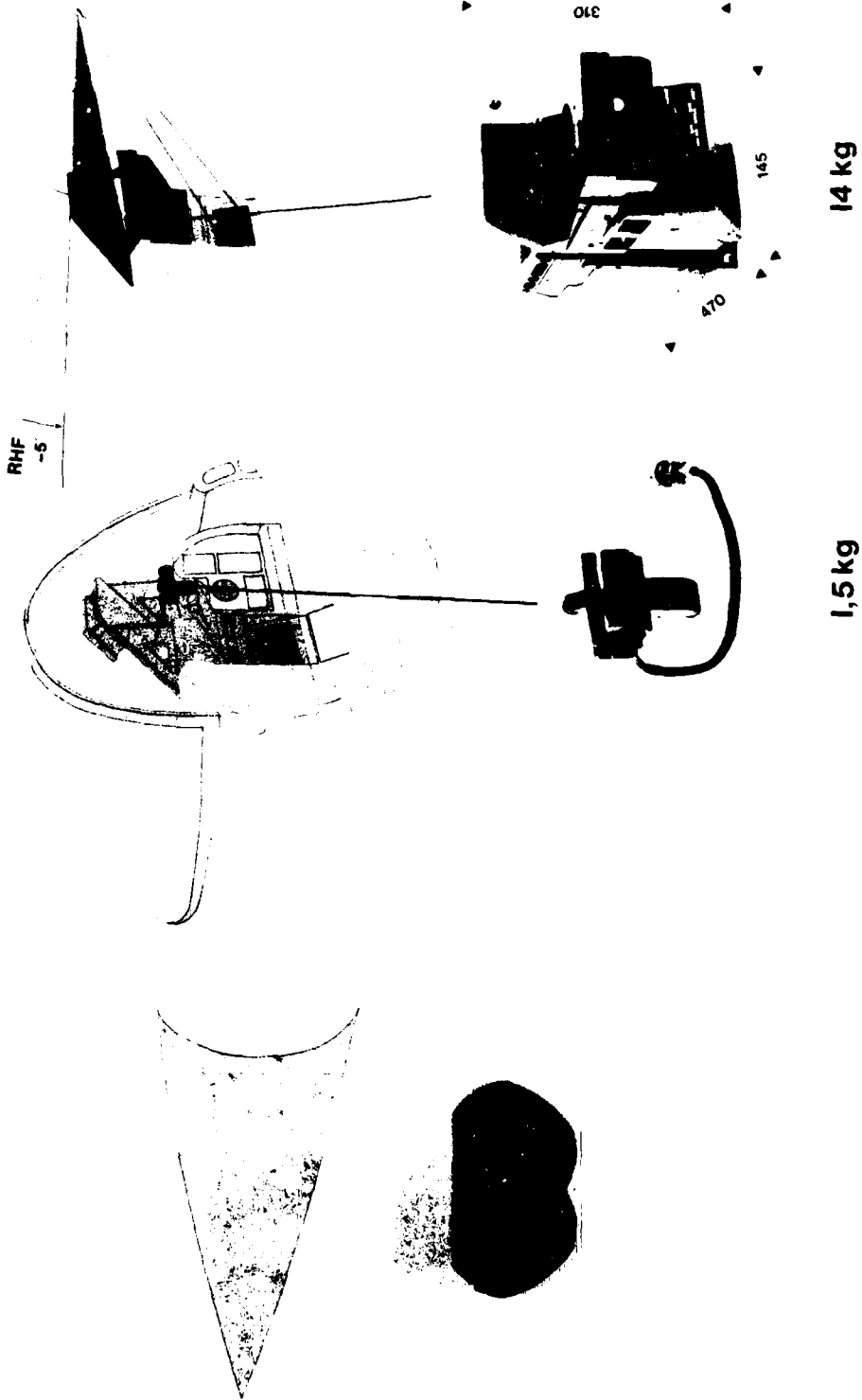


Figure 4

INTEGRATION OF CONTROLS AND DISPLAYS IN U.S. ARMY HELICOPTER COCKPITS

by

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SUMMARY

Integration of controls and displays in Army helicopter cockpits has become mandatory because of increasing demands on the aircrew and constraints imposed on the aircraft cockpit designers. Expanded missions such as anti-armor, night surveillance, and air-to-air, coupled with the survivability requirement of nap-of-the-earth flight, dictate a radical new approach to cockpit design. This approach must apply the latest technological innovations in the areas of controls, displays, multiplexing, and microprocessors to unburden the pilot. Space, weight, and cost constraints placed on the cockpit system designers must also be satisfied. The U.S. Army has recently completed its first full scale engineering development program in the area of cockpit integration, and is currently involved in a more ambitious exploratory development effort. This paper presents an overview of these efforts to integrate the helicopter cockpit, including results of simulation experiments and operational flight tests.

The U.S. Army helicopter fleet consists of gunships, scout, utility, and cargo aircraft which use dedicated controls and displays for each crew function. The need for a radical new approach to cockpit design became apparent during a 1975 aircraft review at which time the addition of required equipment to enhance the capability of a gunship was prevented by the lack of panel space in the cockpit. As a result of this, the U.S. Army embarked on a digital avionic program with the immediate goal of developing an integrated avionic system which would eliminate all dedicated communication, navigation, and identification (CNI) control and display units (CDU's) from the cockpit. The CNI equipments were viewed as a well defined set whose control and display functions could be integrated at minimal risk. After in-house government experiments, which provided the expertise needed to prepare a functional specification, the Army made a major investment in cockpit integration hardware. This effort resulted in the AN/ASQ-166 Integrated Avionics Control System (developed by Rockwell Collins and Grumman Aerospace). The integrated CDU developed can be used in in-service or developmental aircraft to alleviate space problems, reduce pilot workload, and increase CNI capability.

The next step was the initiation of an exploratory effort to determine to what extent the integration concepts used successfully in the CNI area could be applied to the remaining cockpit functions. A four-phase effort consisting of design, hardware fabrication, system integration, and testing was established. A cockpit was synthesized for the BLACK HAWK helicopter in which all crew functions were accomplished using multifunction interactive controls and displays. The results of this effort (performed by Sperry Flight Systems and Bell Helicopter) are presented, together with the status of the hardware currently in fabrication and the Army's plans for bench and flight testing. This exploratory effort is called the Army Digital Avionic System (ADAS).

1. INTRODUCTION

The idea for integrating controls and displays in Army helicopter cockpits was first considered at Fort Monmouth in the early 1970's. At that time the Army was conducting experiments in night nap-of-the-earth flight using a variety of sensors (night vision goggles, forward looking infra-red, rotor blade radars, etc.). Early in these experiments it became evident that crew workload was approaching undesirably high levels. In addition, many of these sensors required new dedicated cockpit displays and controls to be added to the already overcrowded cockpit. In this era, the helmet mounted display became an attractive alternative to an instrument panel mounted display for pilot night vision (FLIR, L³Tv) and flight information. While the helmet mounted display provided some relief for the cockpit real estate problem in the area of pilotage, the need for cockpit space for displays and controls for other new equipment (target acquisition designation systems, aircraft survivability equipment, etc.) continued to grow causing a concomitant growth in crew workload.

In 1974, an experimental program was conducted in-house to investigate the feasibility of integrating the controls and displays of the four communication radio functions normally required in Army helicopters (two VHF-FM, one VHF-AM, and one UHF-AM). The program was structured to capitalize on the emerging technology not only in the control/display area, but also in the areas of digital processing and time division digital multiplexing. Figure 1 shows the control/display unit fabricated under this effort. In addition to providing a centralized means of control and display for the four functions, the system provided up to 20 pre-set channels for each radio (a function not contained in the standard radios of the 1970's). Making the pre-sets available together with the centralized control and display was intended to reduce crew workload. No attempt was made in this preliminary effort to solve the problem of reading electronic displays under bright sunlight conditions.

After bench demonstrations at Fort Monmouth, the unit was used in demonstrations to Army helicopter pilots at Fort Rucker, Alabama, helicopter program managers in St. Louis, Missouri, at Bell Helicopter, Dallas, Texas, and Hughes Helicopter, Culver City, California.

As a result of this effort and the demonstrations, it was concluded that pilot acceptance could be obtained for integrated controls/displays provided major human factors requirements such as ease of operation, sun light readability, and night vision goggles compatibility could be achieved. From a program

manager, airframe developer viewpoint it was apparent that the cockpit space savings, as illustrated in figure 2, had to be more dramatic. Impetus for further effort in this area of integrating cockpit controls and displays surfaced in late 1975 after it was determined during a helicopter gunship program review that required additional equipment could not be physically installed into the already over-crowded cockpit. With the impetus thus provided, the Army Avionics Research and Development Activity (AVRADA) embarked on a series of efforts which will result in a fully integrated cockpit being evaluated in the Fort Monmouth laboratory this year.

2. INTEGRATION OF CNI: THE FIRST STEP

In early 1976, a digital avionic program was established in the Advanced Systems Division of AVRADA which had two goals. The first goal was to apply the concept of integrated controls and displays demonstrated in the aforementioned experimental hardware to a subset of functions common to all Army helicopters, the controls and displays of which could be integrated at minimal risk. The integration of this subset would provide an immediate avenue of relief to in-service helicopters which were becoming limited in the area of mission capability improvements due to lack of cockpit panel space and would also be available for new helicopter systems. The second goal was to develop a longer term exploratory program to investigate the feasibility of integrating all remaining cockpit management functions.

To meet the first goal, all functions in the area of communication, navigation, and identification were examined. These functions were common across the fleet and risk is minimized since, for the most part, only switching functions are involved rather than true computation. The final subset arrived at consisted of all the communication radios, the VOR, ILS, marker beacon, ADF, IFF, doppler radar navigation system, and the communication security devices. Integration of the control/display functions for these devices would, on the average, eliminate from the cockpit the equipments shown in figure 3. Typically, the avionic functions in this subset require approximately 260 square inches of cockpit panel space. By applying control/display integration concepts, the above functions can be accomplished in as little as 40 square inches.

An intense effort was then undertaken in AVRADA to develop a specification which functionally described an Integrated Avionic Control System (IACS) from both a cockpit control/display perspective and an electronic architecture perspective. A joint working group was established which included representatives of the combat elements. From this group a number of requirements in the cockpit area were developed. Of significance were the requirements that:

- (1) the integrated system be fault tolerant in the sense of no single point of failure (this applies to both the electronic architecture, including processing, and the cockpit control/display elements),
- (2) the cockpit displays be readable in bright sunlight up to an intensity of 10,000 foot-candles,
- (3) the cockpit displays be dimmable to levels compatible with airborne night vision goggles,
- (4) A capability to switch from one pre-set frequency to another or one pre-set destination to another be provided which does not require the crew member to look at the display.
- (5) a single one line optional status panel be provided which could be mounted near the top of the instrument panel to inform the crewmember as to what frequency would be transmitted on if the keying switch were activated and the state of the security equipment, and
- (6) automation of emergency functions, such as zeroize and guard channel activation be provided to the greatest extent possible.

Decisions were then made in the Department of the Army to solicit industry for an engineering development effort and award two contracts to provide for competition.

The results of the competitive developments which were conducted by Rockwell Collins and Grumman Aerospace are shown in figures 4 and 5.

While the contractors used slightly different technologies to accomplish the objectives, the results were essentially the same. In each case a primary control panel (shown in center of figures 4 and 5) was developed from which all the CNI and associated security equipments could be operated. The cockpit designer had the option of specifying either two primary control panels or one primary control panel and one secondary control panel (shown left front of figures 4 and 5) as a function of crew size or fault tolerance requirements. As specified, the secondary control panel was to provide a minimum capability for emergency situations. The specification requires it to control one VHF-FM radio, one VHF-AM radio, and the ADF as a minimum. Both contractors, however, expanded the capability to include practically all of the functions of the primary. The essential difference is in the one line of alpha-numeric display versus the multi-line capability of the primary. The status panel (shown right front of figures 4 and 5) is a small one line display which provides frequency and mode status information of the active radio. All goals for the system, previously mentioned were achieved. A typical Integrated Avionic Control System installation is depicted in block diagram form in figure 6. Note that all interface between the cockpit and equipment bay is via the standard (MIL-STD-1553) time division serial data bus which is dual redundant. Thus only two twisted shielded pair wires are required to interconnect the cockpit with the equipment bay. The interface units (shown in rear of figures 4 and 5) are used primarily to interface with the controlled equipments.

The development of the primary control panel established a common set of operational rules which the crew can learn in order to operate a wide variety of avionics functions. Previously, as can be seen in figure 3, each equipment had a different method for entering essentially the same kind of data. The displays (CRT in the Collins design and fiber optic incandescents in the Grumman) are sun-light readable, are red for night-time viewing, are compatible with night vision goggles, and are legible in a vibration

environment, such as encountered in rotary wing flight. Both designs use an interactive or paging technique¹.

Both contractors delivered systems to the Army during 1979. The testing of the Integrated Avionics Control System consisted of a functional verification on the AVRADA hot bench, engineering verification in a UH-1H helicopter at Fort Monmouth, and an operational verification in a UH-1H at Fort Rucker, Alabama.

To facilitate installation of the system, pallets were prepared for each contractor's hardware. Figure 7 shows the hot bench set-up. In addition to functional verification, the hot bench set-up was used for pilot training. Figure 8 shows the Grumman system installed in the hot bench cockpit and figure 9 shows the Collins system installed in the UH-1H helicopter. After engineering checkout in the UH-1H at Fort Monmouth, the aircraft was flown to Fort Rucker, Alabama to undergo operational tests. On a flight at Fort Rucker in early 1980, an instrumentation pallet containing a fixed mounted camera, a video tape recorder, and a time code generator was installed (see figure 10).

The test objectives at Fort Rucker were to assess (1) the operational feasibility and military utility, and (2) the operational advantage over the present avionics configuration. To attain the second objective, a baseline in a conventional UH-1H cockpit had to be established.

The methodology used in this operational flight test² depended on player questionnaires and time-motion studies to conduct the required assessment. Twelve player pilots were used. All twelve flew the standard UH-1H to establish the baseline, then six flew the Collins system and six flew the Grumman system. A 90-minute typical attack mission was used consisting of three 30-minute phases. The first phase was administrative, flown at 1,000 feet altitude. The second phase was low-level flight, at 25 to 50 feet above ground level. The third phase was nap-of-the-earth, flown as close to the earth as terrain and vegetation permitted. Each pilot was assigned twelve tasks per phase. Each pilot performed six manual tasks and six preset tasks with the integrated system, and twelve manual tasks with the standard system. Night flights were conducted using all the controlled avionics and comparisons made (via a subjective questionnaire only) to the standard system.

Assuming time to be a valid measure of pilot workload, the time motion studies (day flight only, 90-minute flights, 36 trials) indicated a significant decrease in workload using the full capability (including pre-sets) of the integrated system. The mean response time to complete a required task for the integrated system (18 trials for each contractor's version) was 3.88 seconds as compared to 6.72 seconds for the standard system. When tasks were performed manually (no pre-sets), no significant increase or decrease in workload was measured. The subjective workload data indicated that all pilots (100%) felt that crew workload was lessened by use of the integrated system in both day and night flight.

As a result of the operational tests, the United States Army Aviation Test Board concluded:

"The Integrated Avionics Control System provides the pilot a cockpit management system that reduces pilot workload. All avionics can now be controlled from one central location. By spending less time inside the cockpit programming different radios, the pilot is able to perform the demanding tasks associated with (NOE) flight more safely and efficiently."

3. THE ARMY DIGITAL AVIONICS SYSTEM (ADAS)

The next step toward integration of controls and displays in Army helicopter cockpits was to determine to what extent the integration concepts used successfully in the CNI area could be applied to the remaining cockpit functions. In late 1978, a four-phase effort consisting of design, hardware fabrication, system integration, and testing was initiated. For approximately 1 year, the design effort concentrated on applying integration concepts to the UH-1H helicopter. Sperry Flight Systems of Phoenix, Arizona was competitively selected to lead the effort and Sperry chose Bell Helicopter Textron, Dallas, Texas to provide assistance in the area of cockpit design. The Bell cockpit design effort had as its goal the definition of a new integrated Army cockpit responsive to both crew and mission requirements using advanced multiplex and display techniques. The previously developed Integrated Avionic Control System was to be incorporated as a fully integrated avionic subset; however, the multiplex data bus architecture would allow for information interchange between any element of the avionic subset and the entire system. The cockpit configuration synthesized by Bell³ for the UH-1H relied on detailed functional requirements analyses, information transfer analyses, workload assessments, and a survey of Army pilots. The Army Human Engineering Laboratory, Aberdeen, Maryland, provided a detailed mission scenario and also provided information in the area of operational requirements. After an intensive effort lasting approximately 1 year, a cockpit was synthesized which incorporated on a total system basis many of the concepts previously used in integrating the CNI subset. As the results of this synthesis were being assessed and reviewed in the Army, a decision was made to re-orient the effort from the UH-1H to a new production UH-60A BLACK HAWK. The UH-60A is the Army's newest utility helicopter and would provide for a testbed with more weight carrying capability. The new BLACK HAWK was named STAR (System Testbed for Avionics Research) and is now performing the role as a testbed aircraft for the Advanced Systems Division of the research activity. Figure 11 shows the STAR helicopter. Phase 1 of the effort was then extended to reflect the change in helicopter. As expected, the cockpit integration concepts were portable and the differences between the helicopters were readily accommodated by the ADAS⁴. The standard production UH-60A cockpit is shown in figure 12. A mock-up of the ADAS cockpit is shown in figure 13. Two 6.8-inch by 6.8-inch cathode ray tube displays will be mounted on each side of the cockpit to handle flight, interactive control/display, and navigation display functions. The flight display will be used to present basic flight information in an integrated format, along with required caution/warning alarms and procedures.

Normally, the flight display function will be presented on the display directly in front of the crew member selecting the function (outer displays in figure 13). However, the flight display function can be presented on any of the four main displays under reconfiguration conditions. This fault tolerance is a key feature of the digital avionic architecture. The inner CRT's in figure 13 have line select units mounted immediately adjacent on each side. When used with these line select units and the keyboard terminal unit (one each side of center console in figure 13 and figure 14) the two inboard CRT displays can be used to present procedures (normal, test, and emergency), engine and fuel status, transmission and rotor status,

secondary systems status and control, advisory/caution/warning information, aircraft survivability equipment status, navigation status and mode control and a number of other functions such as command instrument system status and control, aircraft performance guides, and communication operating instructions.

The navigation display function will be used to present navigation/map and status information to the aircraft flight crew. Normally, the navigation display function will be presented on the CRT display directly in front of the crew member selecting the function; however, the navigation display function may also be presented on any of the cockpit CRT displays under reconfiguration conditions.

All CNI control/display functions are performed in the Integrated Avionics Control Systems primary control panel located on either side (top) of the center console. The one line status panel is provided for each crew member. At the bottom of the center console (each side) is an intercommunication control system. The remaining cockpit items whose functions were not integrated are: the aircraft control panel (center bottom of console), a digital clock, and from left to right a copilot's stabilator indicator, a standby airspeed indicator, a standby attitude indicator, a standby altimeter and the pilot's stabilator indicator. Not shown in figure 13 but to be included is a standby compass and a radar signal detector indicator. Figure 15 illustrates what information typically would be displayed on each CRT during cruise flight.

The production UH-60A overhead console (partially shown in figure 16) will be reduced to the overhead console illustrated in figure 17.

At this time ADAS is undergoing hardware fabrication (Phase II) by Sperry Flight Systems. Delivery to the AVRADA hot bench is scheduled for the fall of this year. At that time hot bench system testing (Phase III) will be initiated by AVRADA. The key objective of this hot bench testing will be to perform a functional validation to insure that all functions required can be performed. AVRADA engineers will be able to change software as required via a software development station in the hot bench facility. Due to the flexibility of the ADAS architecture, any changes in information format required as a result of the hot bench phase will be able to be incorporated by software modification. At the end of the hot bench evaluation (approximately 1 year), AVRADA will begin the installation of an ADAS system into the UH-60A STAR.

During Phase IV, ADAS will be flight tested in the UH-60A STAR. The AVRADA hot bench will remain configured with the ADAS cockpit to provide a flexible system integration tool whereby future subsystems can be first integrated into the ADAS on the hot bench prior to integration and flight test on the STAR. In the near term systems such as the Army night navigation pilotage system⁵ and the Army multifunction coherent CO₂ laser radar⁶ will be integrated with the ADAS. In the far term it is envisioned that much of the cockpit hardware will evolve as control and display technology advances (e.g., monochromatic CRT to full color flat panel, etc.) and new cockpit subsystems (such as voice recognition and synthesis) will be added to further reduce crew workload. The ADAS (both hot bench and aircraft) provides the U.S. Army Avionics Research and Development Activity with a digital avionic structure for the entire aircraft system which allows for growth and technology advances in all of the various subsystems.

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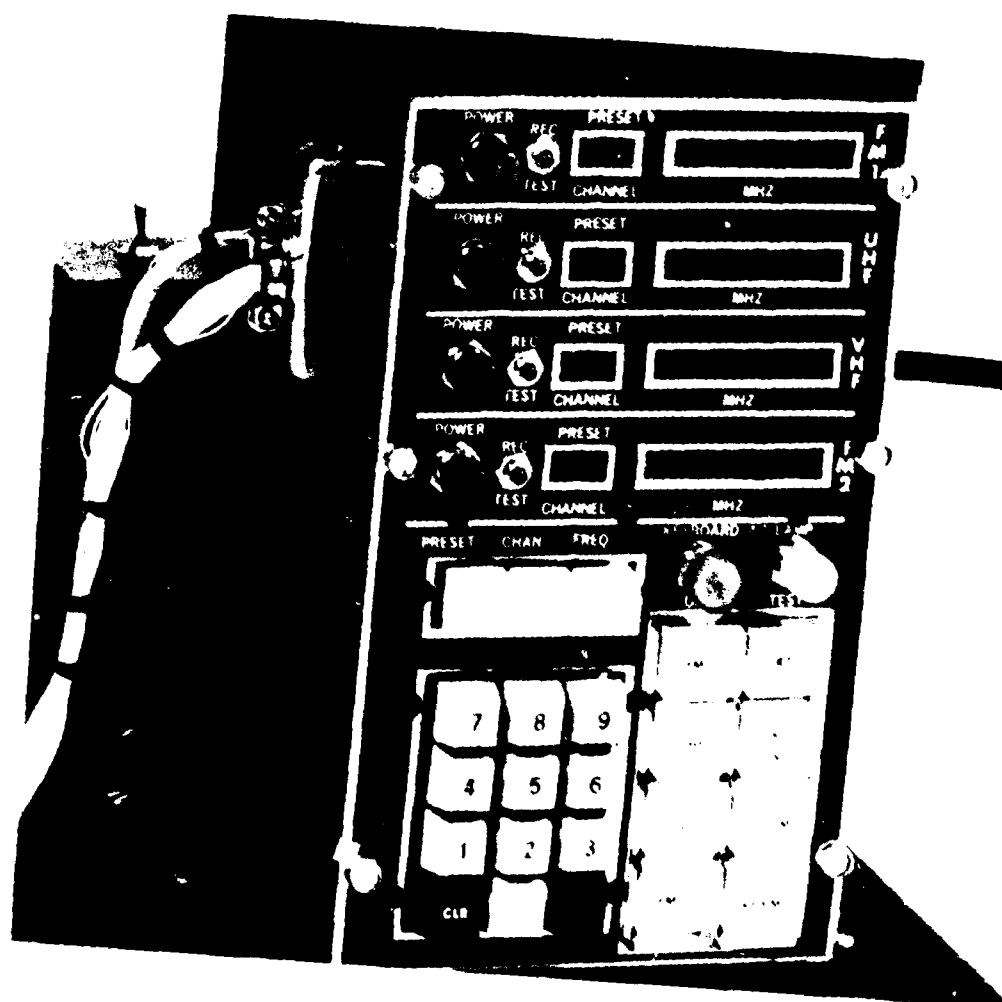


Figure 1. Experimental Control/Display Unit for Communications

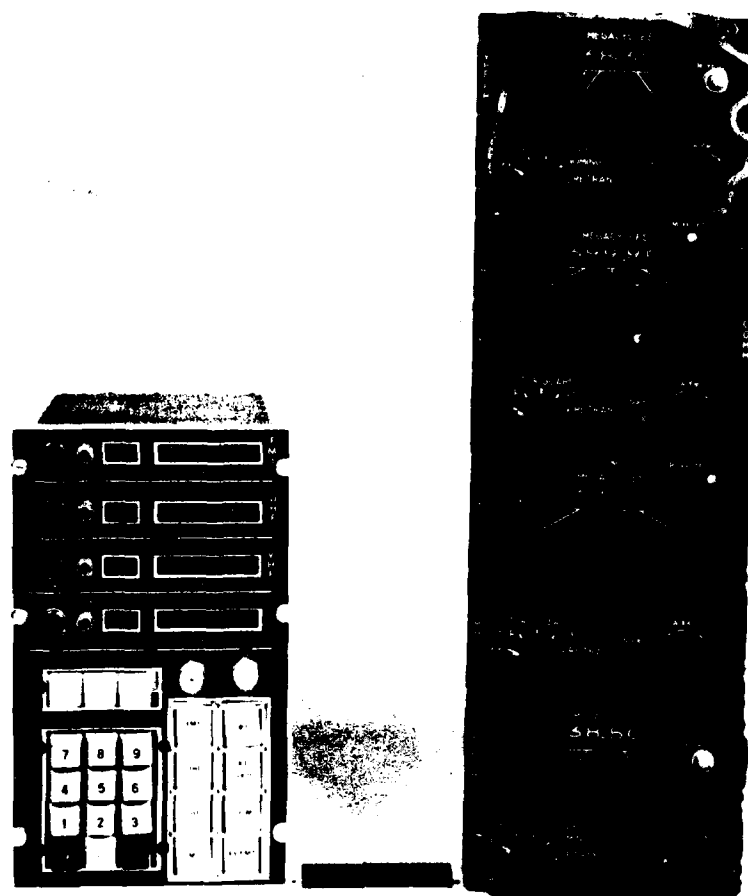


Figure 2. Experimental Control/Display Unit Versus Four Dedicated Equipments

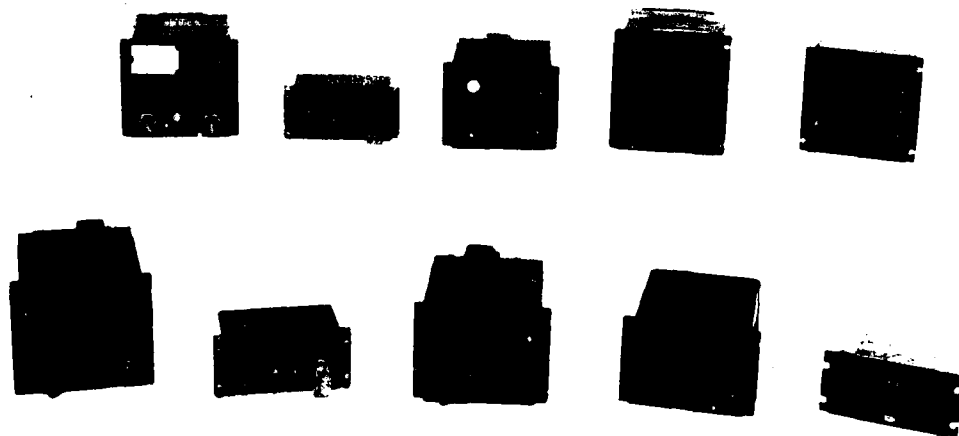


Figure 3. Typical Army Helicopter CNI Controls/Displays

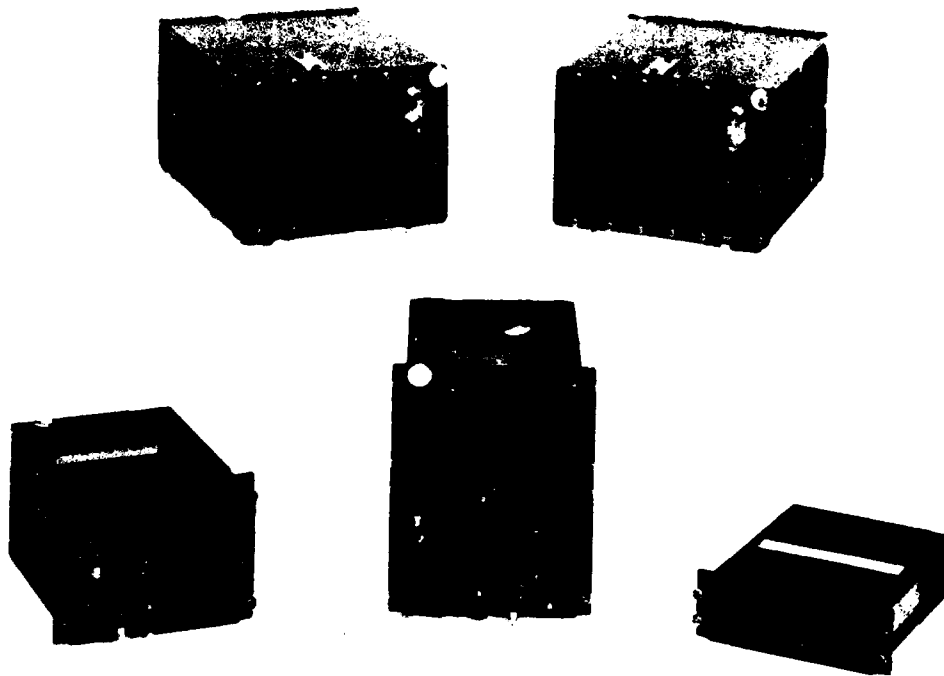


Figure 4. Collins Integrated Avionics Control System, AN/ASQ-166 (XE-2)

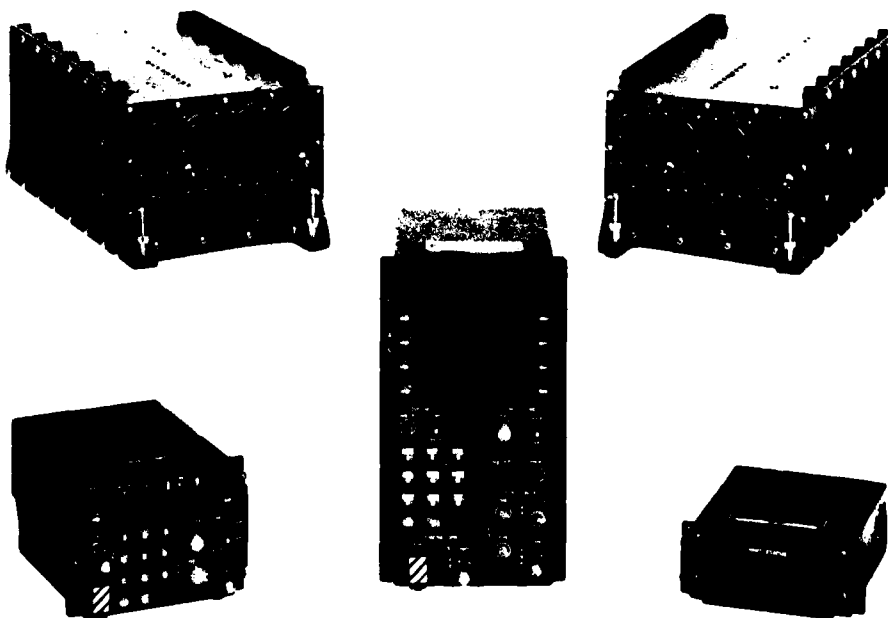


Figure 5. Grumman Integrated Avionics Control System, AN/ASQ-166 (XE-1)

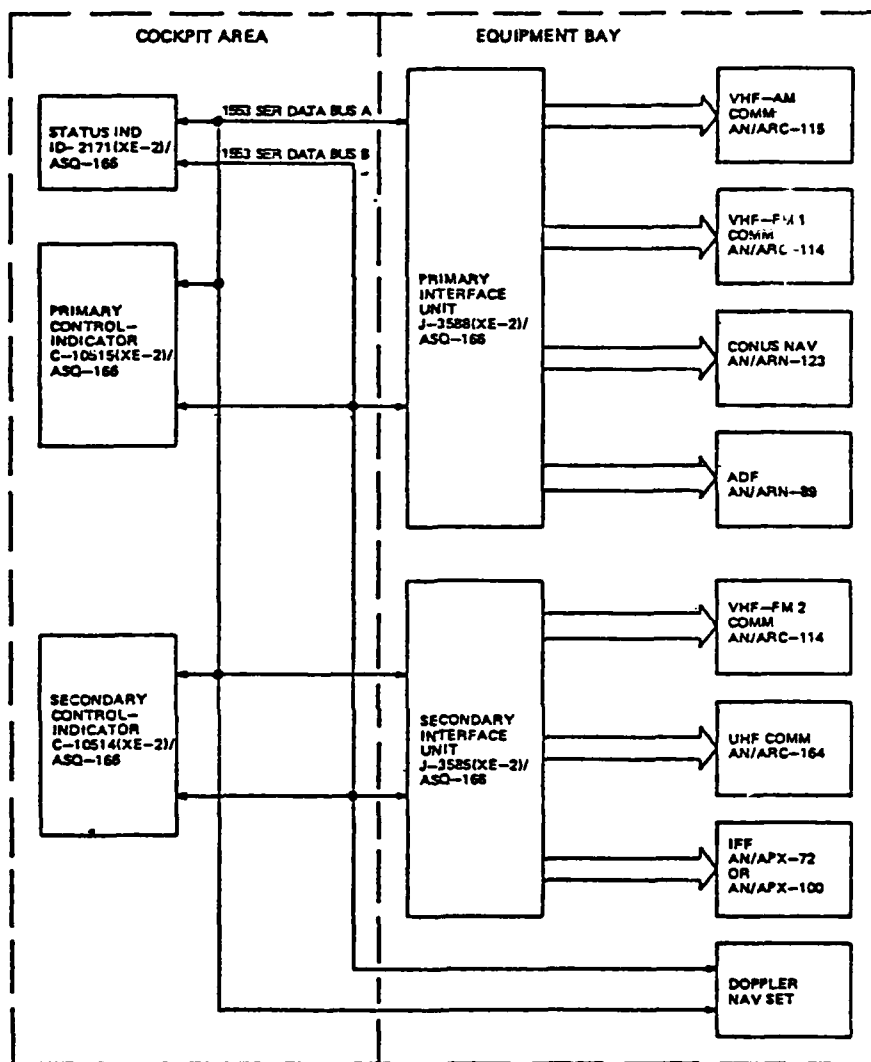


Figure 6. Integrated Avionics Control System, AN/ASQ-166

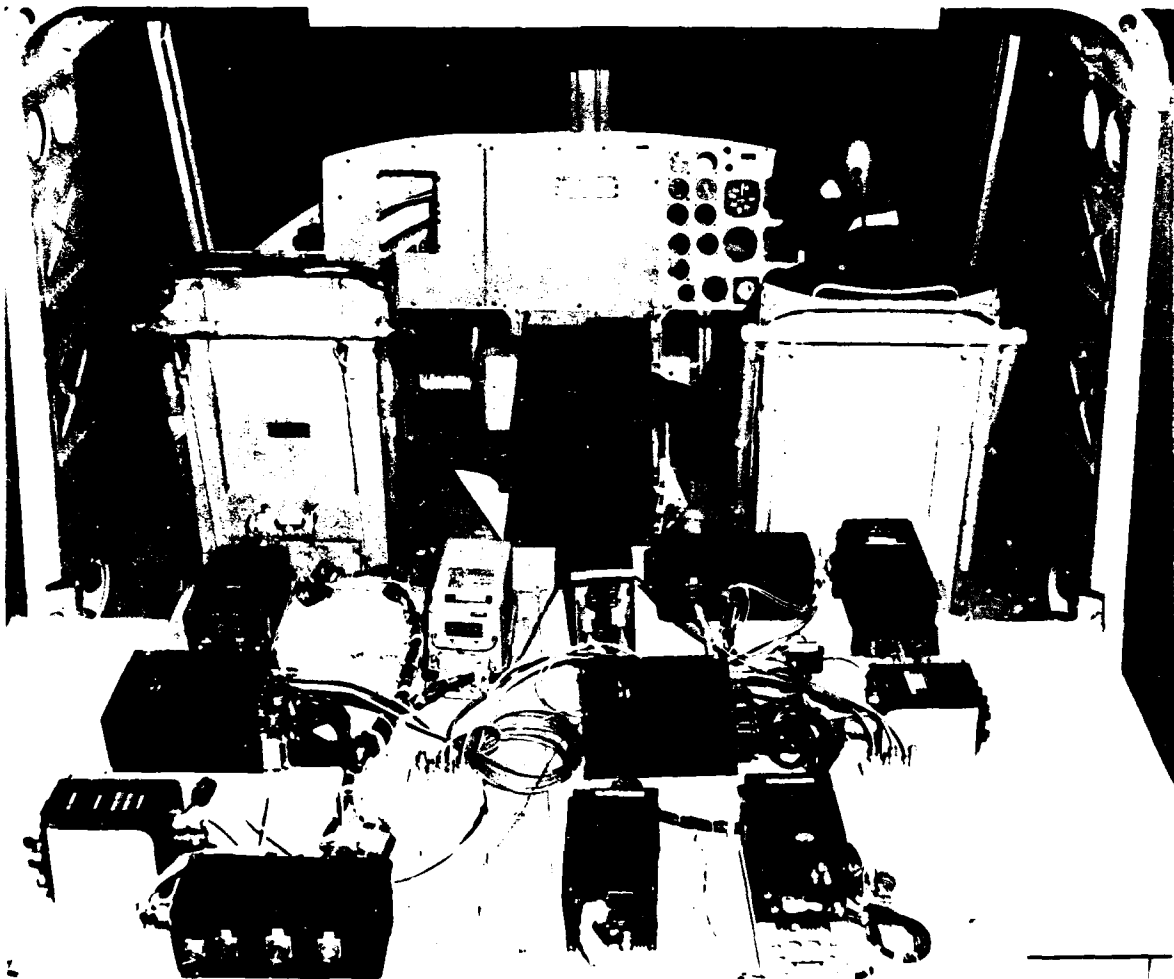


Figure 7. Integrated Avionic Control System Hot Bench

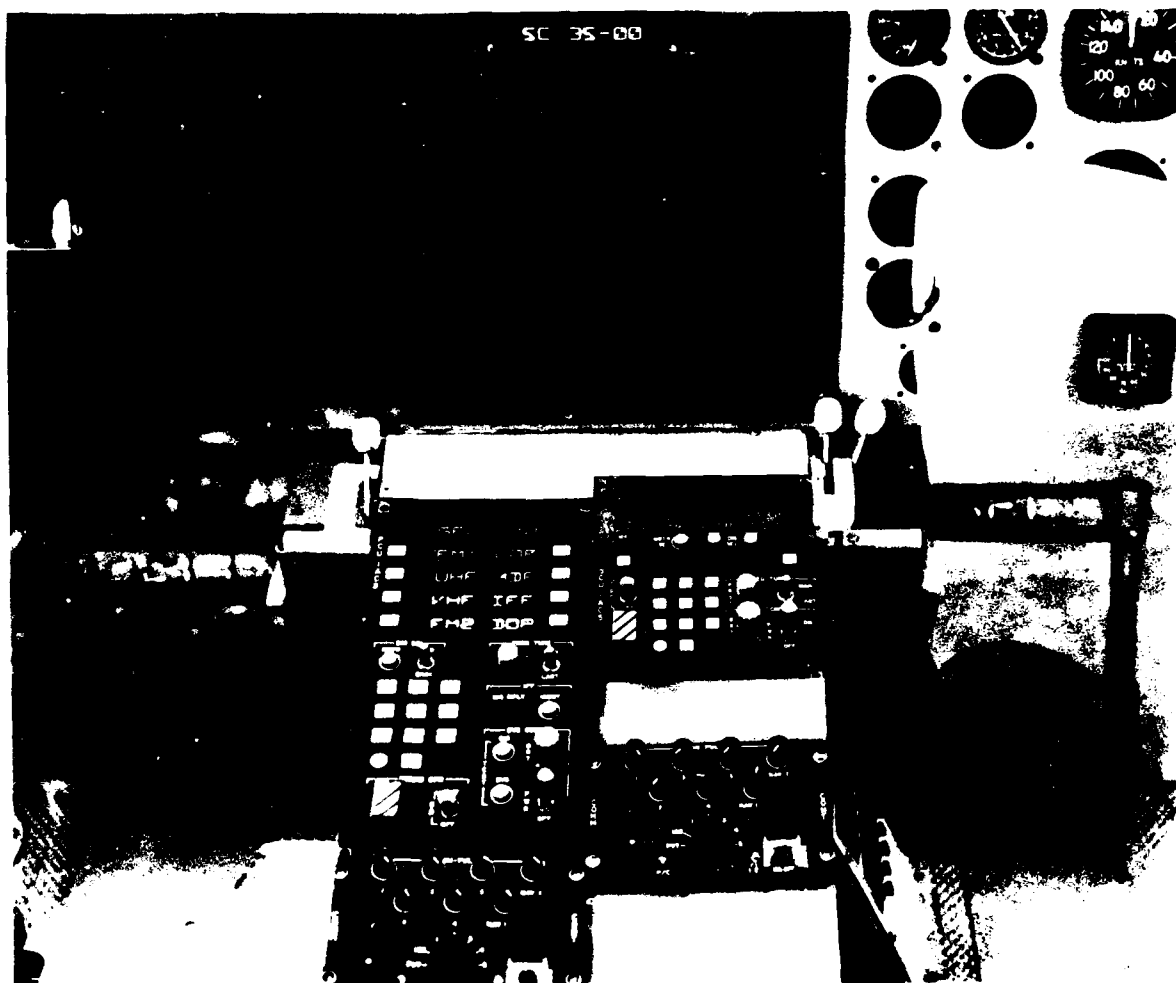


Figure 8. Gruman System in Hot Bench Cockpit

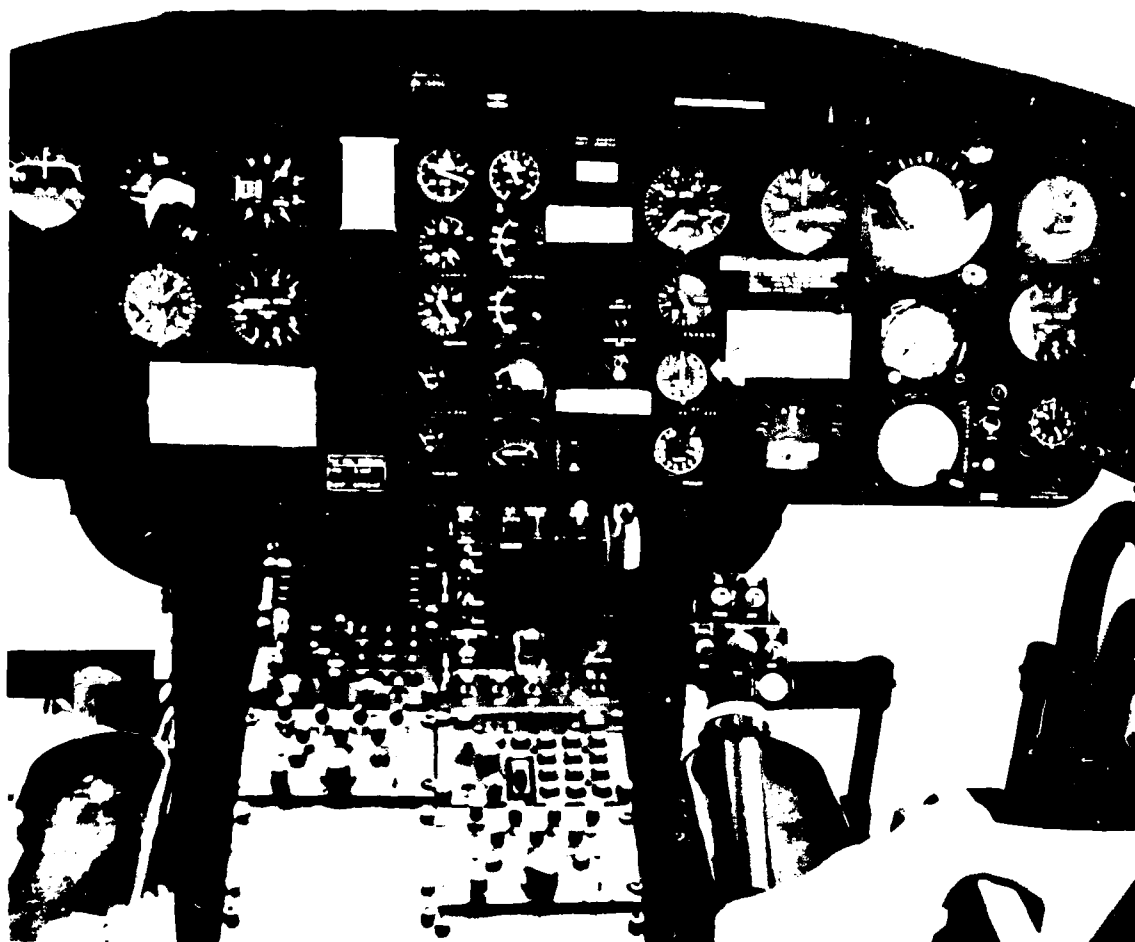


Figure 9. Collins System in Army UH-1H

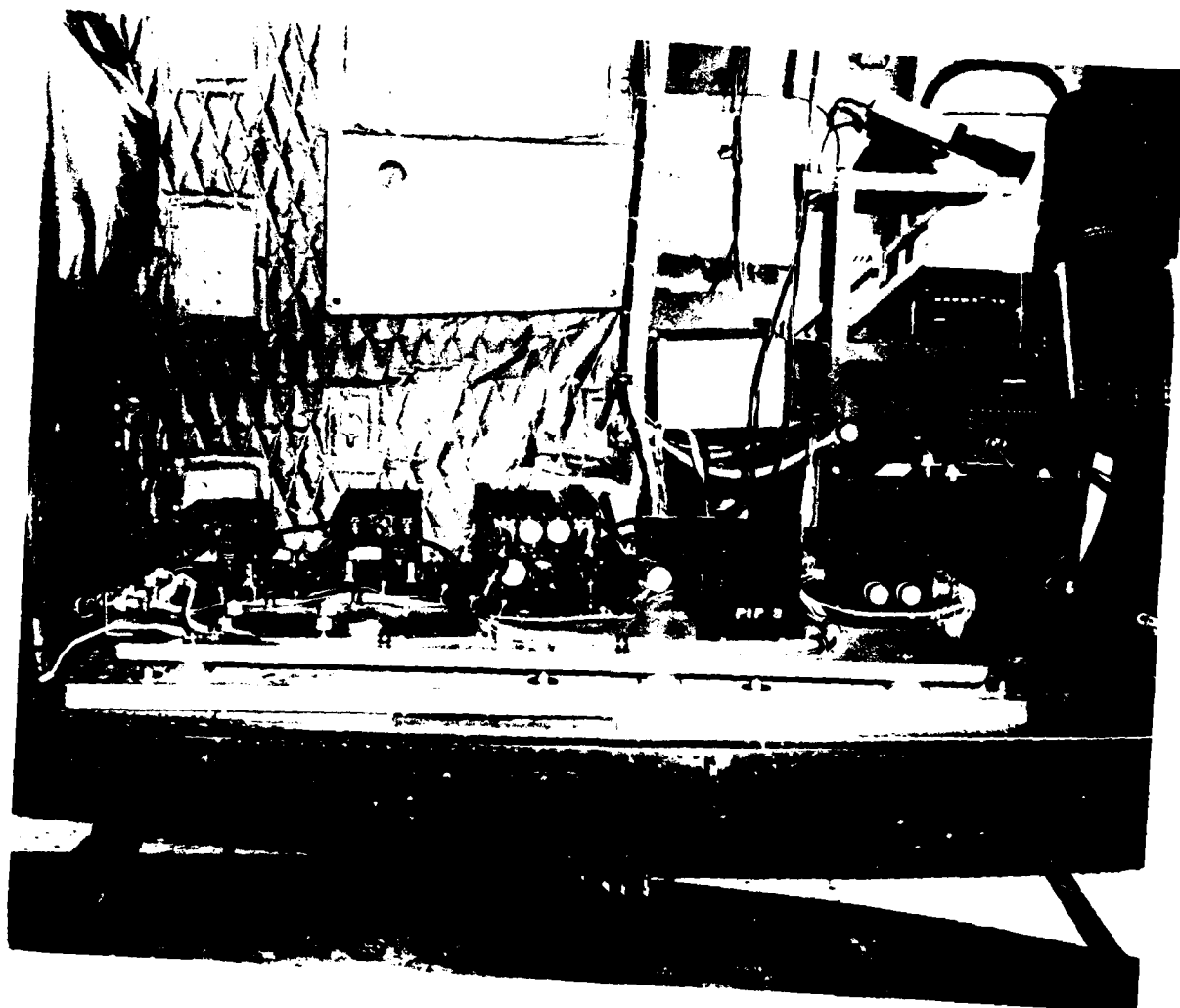


Figure 10. UH-1H With Integrated Avionic Control System (One of Two Pallets) and Fort Rucker Instrumentation Rack



Figure 11. UH-60A STAR (System Test-Bed For Avionics Research)

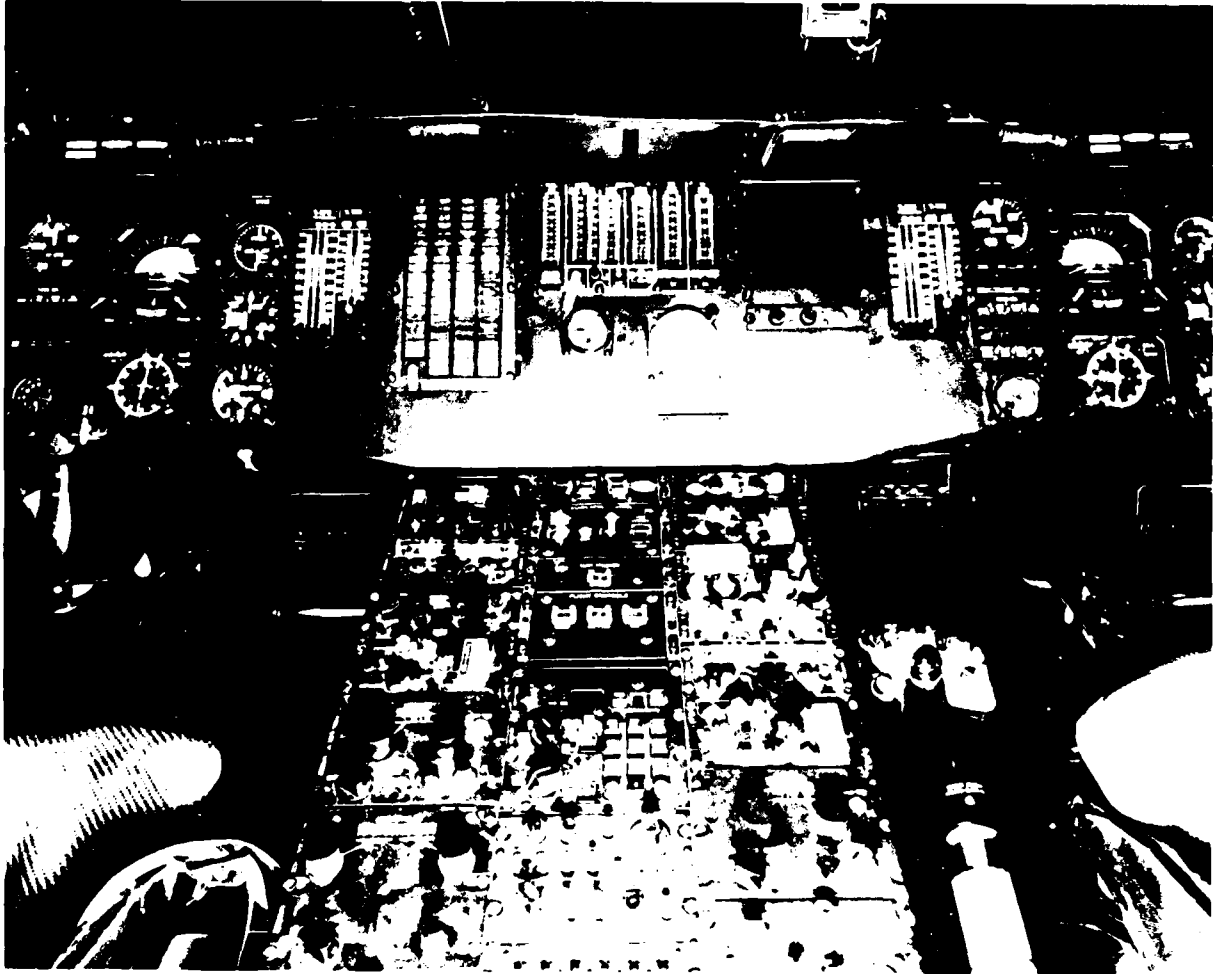


Figure 12. Standard UH-60A BLACK HAWK Cockpit

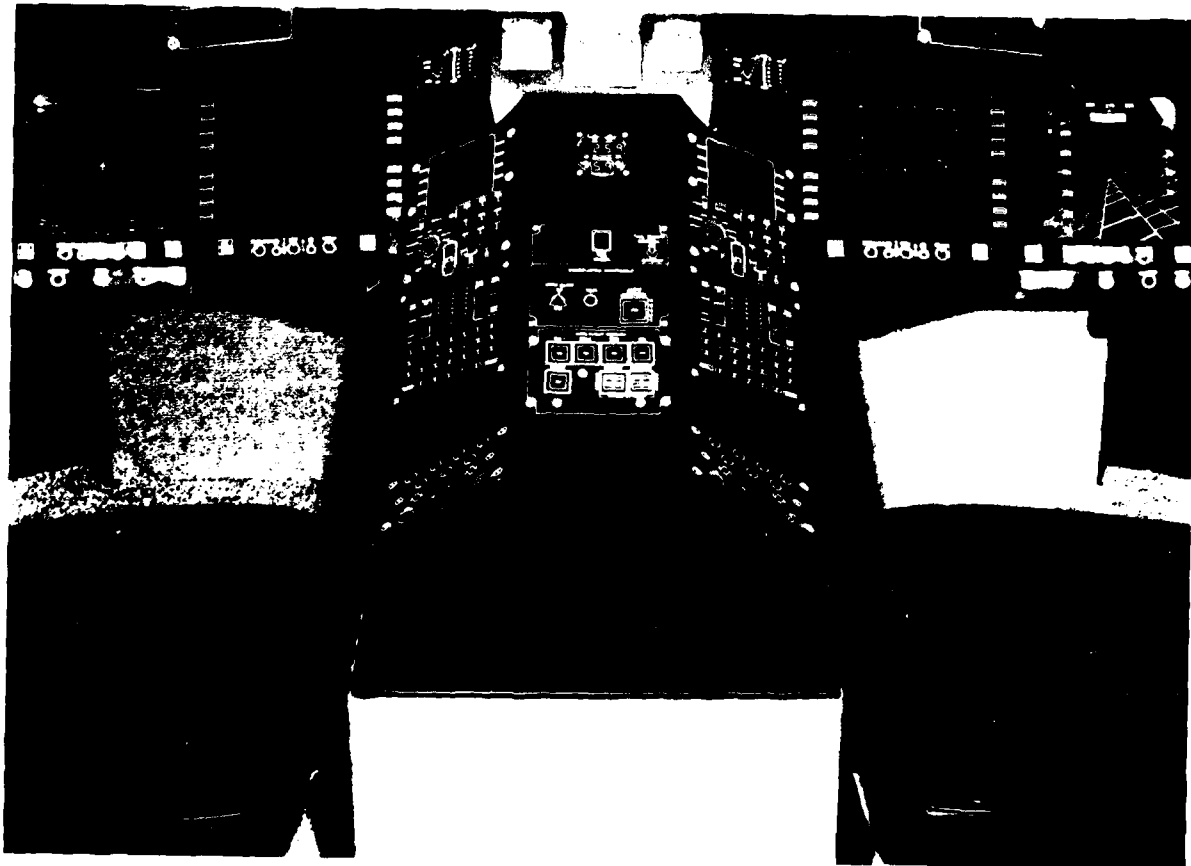
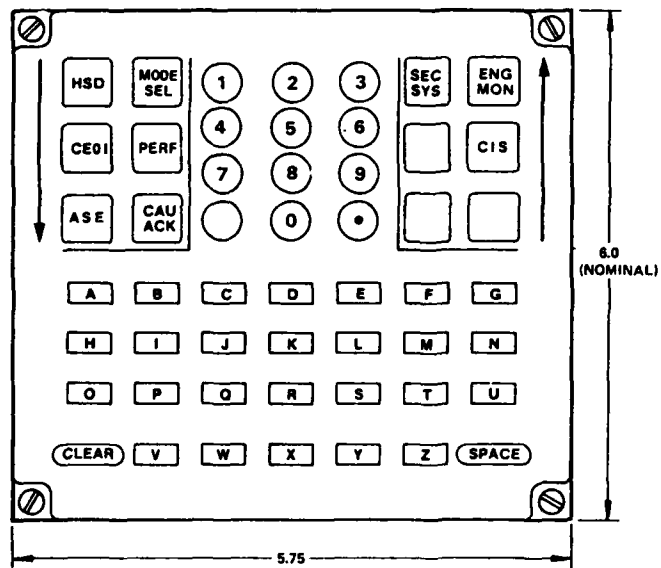


Figure 13. Army Digital Avionic System (ADAS) Cockpit



710-65-14 R1

Figure 14. Keyboard Terminal Unit

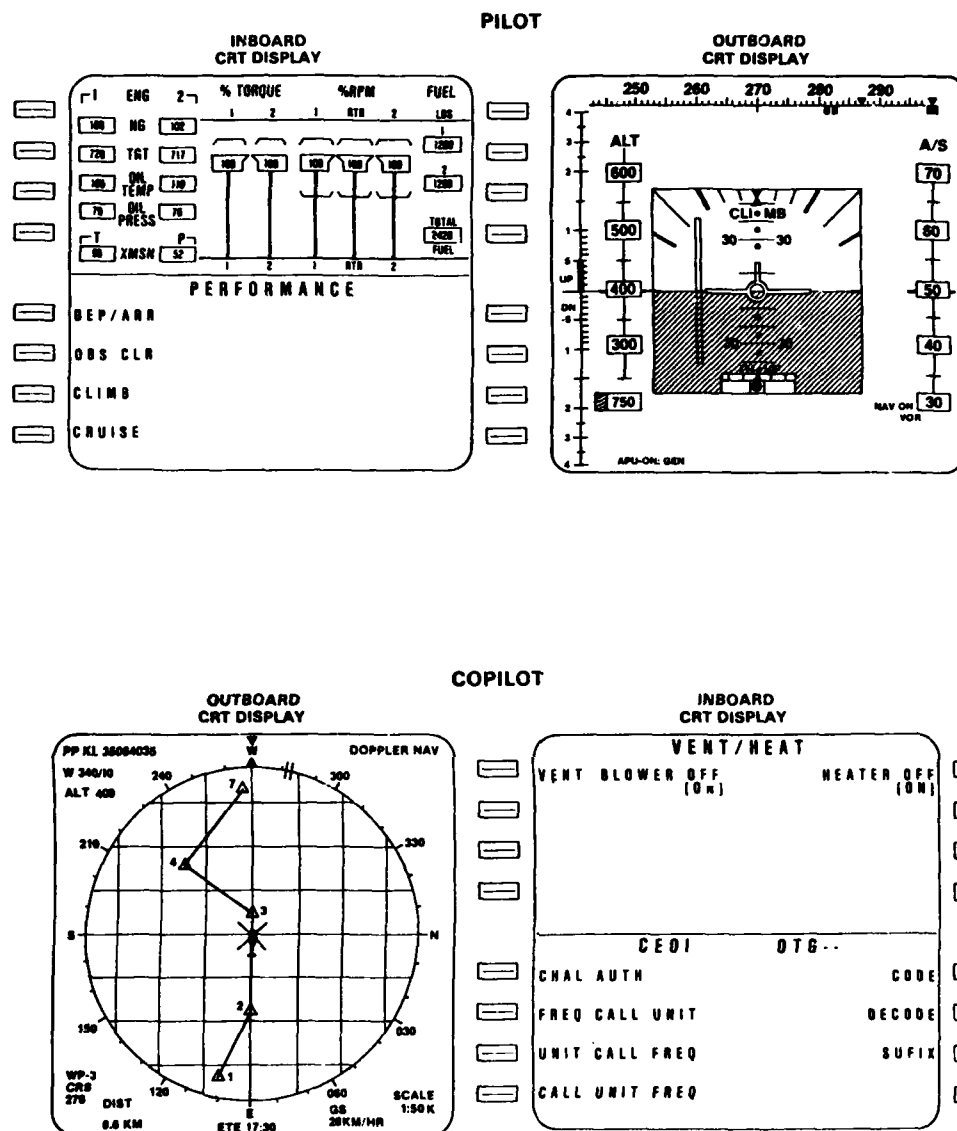


Figure 15. Typical Information On CRT Displays During Cruise

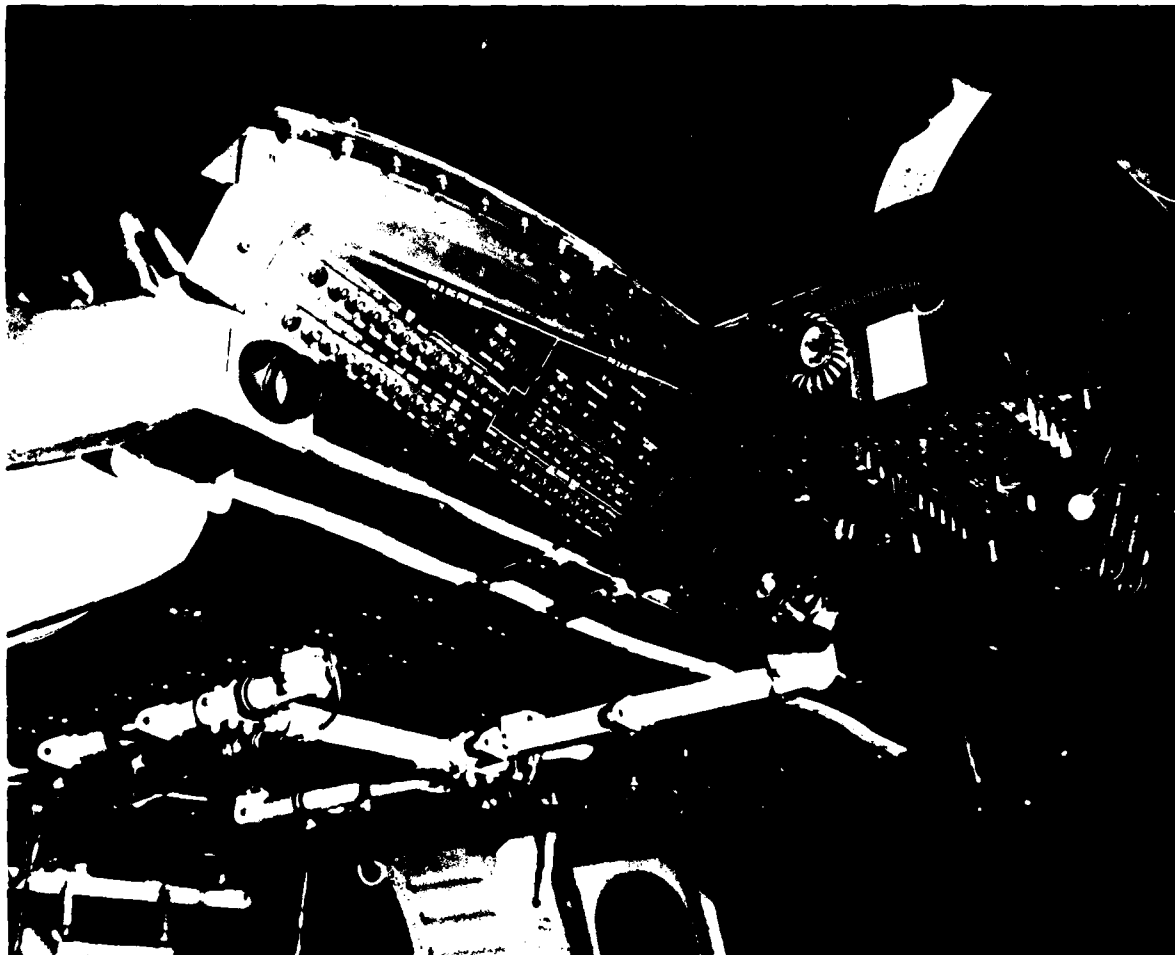


Figure 16. Production UH-60A BLACK HAWK Overhead (Pilot Side)

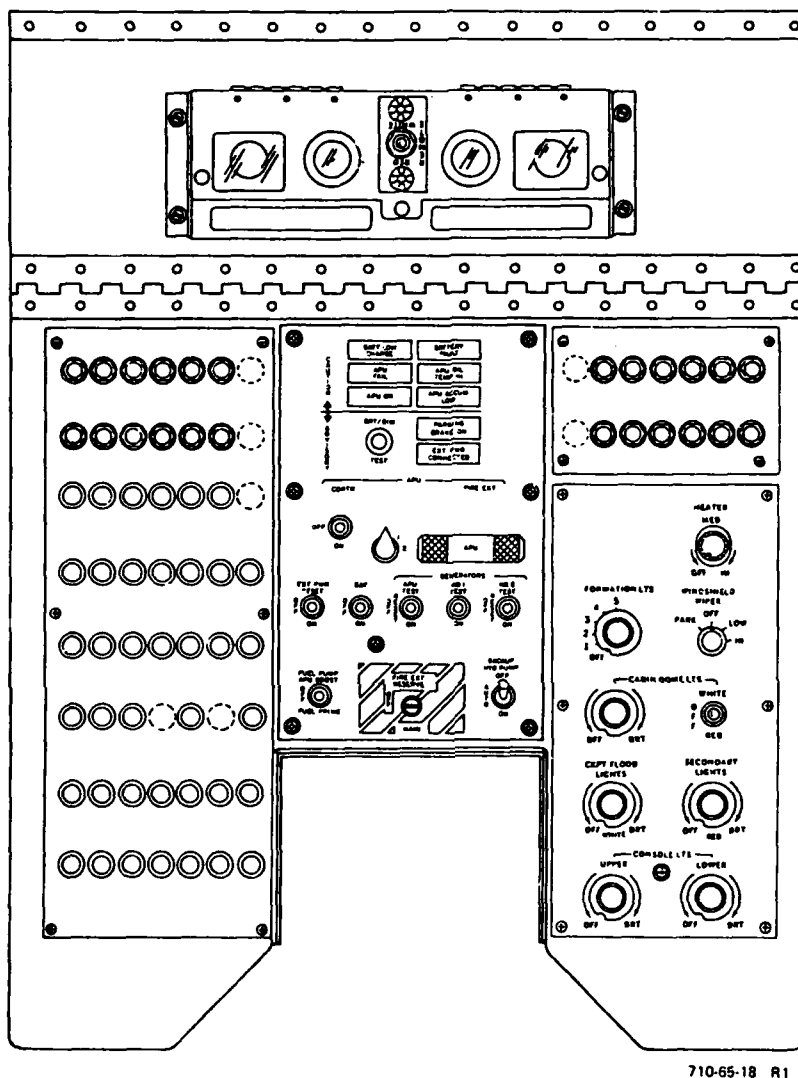


Figure 17. ADAS Overhead Console

A STANDARD CONTROL DISPLAY UNIT FOR MULTI-AIRCRAFT APPLICATION

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SUMMARY

The need for standardization of military hardware is well documented both within the US DOD and NATO. Standardization issues revolve mainly around interoperability, logistics, and life-cycle cost advantages. This paper addresses the issue of standardization and its suitability in the design of aircraft control/display units (CDU). Discussed are potential benefits, requirements, and remaining problems associated with standardization of avionics controls/displays. Included is a discussion of a CDU that is currently being produced which has many of the features considered essential to the ultimate "Standard CDU."

WHAT IS A "STANDARD" CDU?

"Standardized" generally connotes objects built to a rigid set of specifications such that each is identical to the other. In the case where complete interchangeability is necessary, strict adherence to a standard is required. In the case of cockpit controls, where each aircraft type and model have different avionics suites, it is less obvious that standardization can be achieved. This paper addresses several key issues which must be resolved before one can consider "standardizing" to a particular unit. The most important of these is the issue of flexibility vs rigidity. As defined above, "standard" implies "rigid." A need exists, however, for a standard CDU that is flexible enough to be used for multi-aircraft applications. This is desirable because the logistics and life-cycle cost benefits are a function of the size of the aircraft population in which the CDU can be used. The solution to this dilemma and the approach taken by this paper is to concern ourselves with the degree to which a CDU can be standardized. In other words, we want to answer two specific questions:

1. To what level can an aircraft control/display unit be standardized without sacrificing mission effectiveness.
2. What cost benefits are derived by various levels of standardization.

The remainder of the paper is divided into three major sections. The first discusses standard CDU requirements in a general sense. Addressed are issues of physical, functional, and flight crew interface characteristics. The second provides a real-world example of how these requirements were used to develop a CDU for multi-aircraft applications. The third and final section summarizes remaining problems and work that needs to be done in the future.

STANDARD CDU REQUIREMENTS

The ultimate goal of a set of requirements for a standard CDU is to prescribe a unit which has applications for as large a military aircraft population as possible. Consideration should be given not only to fixed-wing aircraft such as fighters, bombers, and transport but also rotary-wing aircraft. Standardizing across aircraft types involves a host of issues which require careful study before a detailed specification can be generated. In the simpler case, for instance, where one is standardizing a sensor for several aircraft, the primary issues are form, fit, and function. In the case of a control/display, however, an additional issue must be resolved - the interface to the flight crew. It is not obvious that a single control/display scheme can be devised that is appropriate for both the spacious cabin of a transport aircraft and the tight, high-g cockpit of a fighter.

Another issue which should impact standard CDU requirements is growth. Once the CDU is installed in a particular aircraft type, it should be assumed that the aircraft will be subjected to a series of product improvement programs over its service life. The impact of this on CDU requirements is to provide for the necessary growth capability which will be needed to control future avionic configurations. The currently popular notion of preplanned product improvement (P³I) is particularly valid in this case. With the above considerations in mind, the following provides an overview of CDU physical, functional, and crew interface characteristics.

A. Physical Characteristics (Form, Fit): Specification of physical characteristics can be done in a relatively straightforward manner. Width and depth should be specified to meet the requirements of appropriate design standards such as MS25212 (5.75 in (146.05 mm) width, 8.0 in (203.2 mm) depth including connector and cable bend). Specification of unit height is a function of available console space within a target aircraft. If we assume that the standard CDU will control functions previously controlled by several dedicated units, it is not unreasonable to expect 6 to 10 in (152-254 mm) of available console space. The desired height, however, in order to assure installation should probably be less than 8 in (203 mm).

Assuming a standard aircraft console installation, the major issue to be resolved in relation to fit is the specification of aircraft connectors. The primary consideration of course is to allow a sufficient number of pins to provide for immediate applications and spares for growth application.

B. Functional Characteristics: Specification of functional characteristics represents a major challenge in development of a standard CDU. This is particularly true for multi-aircraft applications. There are two major functional areas which need to be considered prior to specifying characteristics for a standard CDU: aircraft interface and internal processing.

1. **Aircraft Interface:** It is not possible to discuss a standard control/display for multi-aircraft applications without a standard aircraft interface. A major breakthrough for aircraft avionics standardization has been the development and industry acceptance of the MIL-STD-1553 data bus. This time division multiplex data bus allows up to thirty-two units (remote terminals) to share information, as directed by a bus controller, over a single twisted, shielded pair of wires. Most applications use a dual configuration for redundancy. A major impact of MIL-STD-1553 is that it allows control of multiple units through a single interface. It is the standard interface for the standard CDU.

While MIL-STD-1553 significantly reduces the amount of discrete wires needed to interface with various controlled avionics, there are always some nonmultiplexed functions which are monitored or controlled by the CDU. These functions vary in number and type from application to application but basically implementation is driven by either aircraft wiring convenience or safety reasons. Examples in our experience include interface to encoding altimeters, power control, fault monitoring, fault annunciation, and remote switches. Specification of discrete input/output capability for a standard CDU must be performed with knowledge of both present and future needs. Inadequate definition could result in redesign of CDU circuitry, additional or larger connectors, and possibly an expensive aircraft retrofit program.

2. **Processing:** An important consideration in the specification of a standard CDU is the amount and type of data processing to be performed. In other words, how "smart" should the CDU be? A "dumb" CDU takes information from the multiplex bus and displays it as received. Control inputs from the front panel are sent directly out on the bus with no transformation. In the simple case, for example, where it is desired to make a numeric input and have it displayed on the screen three steps are necessary. First, the CDU senses that a numeric key has been pressed and sends the information out over the bus to an external computer. Second, the external computer receives the information, converts it to the proper display format, and sends it back to the CDU. Third, the CDU receives the information and displays it.

By incorporating a processor in the CDU a "smart" CDU is created giving the avionics systems designer added flexibility in terms of how processing functions will be distributed within the aircraft system. For instance, in the example presented for the "dumb" CDU, a numeric input could go directly from keyboard to display without transmission over the bus. The level of intelligence contained within the CDU is up to the designer. It is now well within the realm of possibility, for example, to supply nothing more than aircraft heading and velocities to a CDU, have the CDU compute a navigation solution, and display it to the flight crew.

The degree of intelligence which one would specify for a standard CDU is subject to a considerable number of trade-offs. A smart CDU has the advantage of increased systems design flexibility, reduced bus loading, and the capability of implementing special functions such as built-in-test. However, a disadvantage, which requires careful consideration, is the need for software. In any particular aircraft implementation, a smart CDU will probably contain software which is specific to that aircraft. This is true because each aircraft type will have a different avionics complement and therefore require unique control/display software. Ultimately the decision concerning the desired level of internal processing capability should be based on target aircraft operational requirements, and life-cycle cost trade-offs of increased flexibility vs nonstandard software.

C. Crew Interface Characteristics: The requirements for a standard CDU must obviously also include the type of desired controls and displays. In general, the display requirements must address:

1. Type of Medium (CRT, Incandescent, LED, etc)
2. Color (red, blue-white, green)
3. Size of Characters (ensure legibility under vibration)
4. Viewing angle (at least $\pm 45^\circ$ in both axes)
5. Day/Night Readability (10,000 ft L to 10^{-3} ft L ambient)
6. Number of Characters
7. Annunciators (number and type)

How these issues are addressed specifically depends on the number and type of functions which the CDU will be expected to perform. It is essential, however, that the requirements be consistent. For example, size and number of characters must be consistent with the allotted panel space.

A more difficult requirement is the specification of a generalized set of controls. Some of the issues which must be resolved are:

1. **Tactile Characteristics:** Consideration must be given to the conditions under which control inputs will be made. Is heads-up operation required? Will control inputs be made during high-g maneuvers? What special requirements are necessary to ensure gloved-hand operability? These conditions will all have a significant impact on how a control panel is designed.

2. **Data Entry Characteristics:** Another important consideration is the type of data which is to be entered. Data type is particularly important in the design of keyboards. Is alpha data entry required? If so, how often and during what phase of a mission is it entered? These questions must be asked in order to determine whether a dedicated full alpha keyboard is necessary or whether a condensed alphanumeric keyboard is sufficient. Also, definition must be provided for any special characters (+, -, ., etc) which are required.
3. **Dedicated Controls:** Each application will have requirements for controls which are dedicated to specific functions. Basically, these include controls for such functions as power, emergency, and mode. Considerations important in the specification of these controls include requirements for guards, barriers, locks, and placement relative to other controls to prevent accidental activation/deactivation.

The generation of a set of control requirements based on the above considerations is usually not difficult for any particular application. For multi-aircraft applications, however, it is extremely difficult to specify a single set of controls which will not only satisfy the requirements for a variety of avionics suites but also satisfy the crew interface requirements for the vastly different flight regimes of the fighter and the transport aircraft.

REQUIREMENTS SUMMARY

The previous section provided a brief discussion of requirements for a standard CDU. In brief, the highlights of this discussion were:

- (a) **Form:** Width 5.75 in (146.05 mm); Depth no more than 8.0 in (203.2 mm) including connector and cable bend; height less than 8.0 in (203.2 mm).
- (b) **Fit:** Ensure connector(s) provide a sufficient number of pins for immediate multi-aircraft requirements plus growth.
- (c) **Interface:** MIL-STD-1553 plus well researched definition of nonmultiplex interfaces.
- (d) **Processing:** Make LCC trade-offs of enhanced flexibility vs nonstandard software.
- (e) **Display:** Consider medium, color, character number/size, viewing angle, readability, and annunciations. Make sure requirements are consistent with available technology.
- (f) **Controls:** Goal is to meet multi-aircraft requirements without sacrificing mission effectiveness.

These are basically general requirements for consideration. How they are applied in the generation of actual hardware is described in the next section.

EVOLUTION OF A ROCKWELL STANDARD DESIGN

Rockwell's background in the design and development of general purpose CDU's began in 1966 when the Navy's Tacamo (8835B-1) control/display unit (CDU) was produced and continued in 1970 when the 813H-1 CDU was produced for a commercial area inertial navigation system. These displays were general purpose in nature with little or no intelligence. The 813H-1 display was basically a "chalk board" which reproduced whatever came into the unit via a nonstandard digital bus. Nonstandard in this context means the bus was designed for a particular application. This CDU was also larger than would be appropriate for a present-day standard. It did, however, provide a degree of standardization to the factory production line because new applications could be satisfied by merely redefining the front panel and possibly changing the input/output characteristics. The thrust was to design a modular CDU which would minimize production line impact and nonrecurring development costs when changes to meet new applications were necessary.

In 1976 Rockwell was awarded a development contract by the US Army for the Integrated Avionics Control System (IACS). This system, which was slated as a standard system for Army helicopters, integrated the control of all communication and navigation radios into a single CDU and remote processor. A second smaller control head was also provided for limited backup control. The interface between units was defined as a MIL-STD-1553 multiplex data bus. It was at this time that we first considered the possibility of a standard CDU. If the IACS system were defined to allow for a CDU which contained no aircraft specific functions, a generalized CDU would result. Additionally, the use of a MIL-STD-1553 data bus, which was gaining industry acceptance, added credibility that a standard CDU could be achieved. Support for this notion came through avionics development programs subsequent to IACS. We found that these programs also had a requirement for a flexible control/display similar to the IACS CDU. In brief, these programs include:

- (a) **The United States Coast Guard HC-130H Aircraft:** provides control and display of UHF, VHF, HF, and VHF-NAV radios; IFF; and display of inertial data.
- (b) **The United States Coast Guard HU-25A Medium Range Surveillance Aircraft:** provides control and display of UHF, VHF, HF, VHF-NAV, TACAN, and ADF radios; IFF; and participates in the transfer of radar fixes to the navigation system.
- (c) **The United States Coast Guard HH-65A Short Range Recovery Helicopter:** provides control and display of UHF, VHF, HF, VHF-NAV, TACAN, and ADF radios; IFF; LORAN; Data Link; and displays Engine Condition Monitoring System data.
- (d) **Lockheed L-1011 Model 500:** provides control and display functions for the Digital Flight Control System.
- (e) **The United States Air Force A-10 Aircraft:** provides control and display functions for the Standard Inertial Navigation Unit and aircraft built-in-test (BIT) as well as aircraft MIL-STD-1553 multiplex bus system test.
- (f) **The United States Army Special Electronics Mission Aircraft (SEMA):** provides control and display of the inertial navigation system and TACAN; and performs backup control of the MIL-STD-1553 multiplex data bus in case of failure of the primary controller.

The first four CDU's are essentially identical to the IACS CDU with the exception of the front panel control configuration. The last two units (A-10 CDU and SEMA CDU) are similar with the exception that for these applications a microprocessor was incorporated in the unit to provide display formatting and data manipulation capability.

The thrust of the following paragraphs is to provide a brief description of the process through which these CDU's were developed. Although presented only in their final form, the design requirements were refined during a period of over five years.

ROCKWELL CDU DESIGN APPROACH

The first step in the process of developing a Rockwell standard design was to determine the requirements which were essential for a useful, truly standard unit. In addition to normal cost considerations these were:

- (a) Sufficient data display capacity which has good sunlight and night vision goggle readability.
- (b) Versatile front panel controls which are easily modifiable.
- (c) A size which would fit most aircraft installations.

In addition to these requirements it was desirable to have processing capability in the CDU to accomplish the following:

1. Allow the CDU to act in a stand-alone manner so that it could perform a given function without the use of an external computer.
2. Improved built-in-test which could isolate to the card or module level to minimize support equipment and personnel requirements.
3. MIL-STD-1553 multiplex bus control capability.

The following paragraphs describe how the CDU design evolved to meet the above requirements.

CDU Display Capacity/Type

Early in the investigations to determine display capacity a basic question was asked concerning whether a small amount (one or two lines) of display information was sufficient or whether a mass media type of display was required. This question was key because if only a few characters were required to accomplish the needed functions then less expensive segmented displays such as incandescent, LED's, etc could be considered. If, however, a significantly larger amount of display data was required at one time, more expensive mass media displays such as CRT's or flat panel displays, would be required. In a short time it became obvious that the increased operational problems associated with utilizing a small amount of display were too severe to justify the cost savings. These problems were centered around the added number of control inputs that a pilot would have to go through to accomplish a given task. For example, consider a presently existing CDU for an inertial navigation sensor which has only two lines of display six characters long. Many parameters need to be displayed such as present position, magnetic and true heading, magnetic variation, ground speed, airspeed, steer points, wind direction, and wind velocity to name a few. It is obvious that no more than two of these parameters can be displayed at one time due to the display limit. For this reason, reading a given parameter is not simply a matter of glancing down into the cockpit to read a display but becomes a three step process where the pilot must read the mode of the display, push a button or rotate a knob to select the desired parameter and then read that parameter. Another problem caused by limited display capacity is that during data entry, only entered data is displayed precluding access to monitored data. Additionally, since the standard CDU concept will undoubtedly lead to higher levels of system integration due to its accessibility by other systems via the MIL-STD-1553 multiplex data bus it was deemed necessary to include additional display capacity to accommodate these additional functions.

To determine the optimum amount of information displayed at one time, various potential higher level applications were considered. These included:

1. Flight Control
2. Navigation
3. Communications/Identification
4. Systems Monitoring
5. Target Acquisition/Weapons

The next step was to determine which parameters needed to be displayed for each of these applications. In addition, some method needed to be defined to control various system modes. These parameters and control functions were listed in the order of importance or level of use to the pilot. In virtually every case it became apparent that it was desirable to have all the information for a given mode displayed at one time to reduce pilot workload. Although it was decided that the optimum amount of displayed data was "as much as possible" the final result was to specify a display of 8 lines, each with 19 characters. This amount was arrived at by trading off what data the pilot needs at a given time, the number of switch activations the pilot must make to obtain any and all information, the number of characters needed for each data type, and what amount of data could be provided in a CDU of reasonable size. The desired amount of display data capacity was then utilized to accomplish comparisons between existing display technologies in areas including cost, display quality, environmental conditions, and reliability. The result was the selection of the CRT utilizing stroke written characters. This decision was reached for a variety of reasons.

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THE IMPACT OF NEW GUIDANCE AND CONTROL SYSTEMS ON MILITARY AIRC--ETC(U)
AUG 81

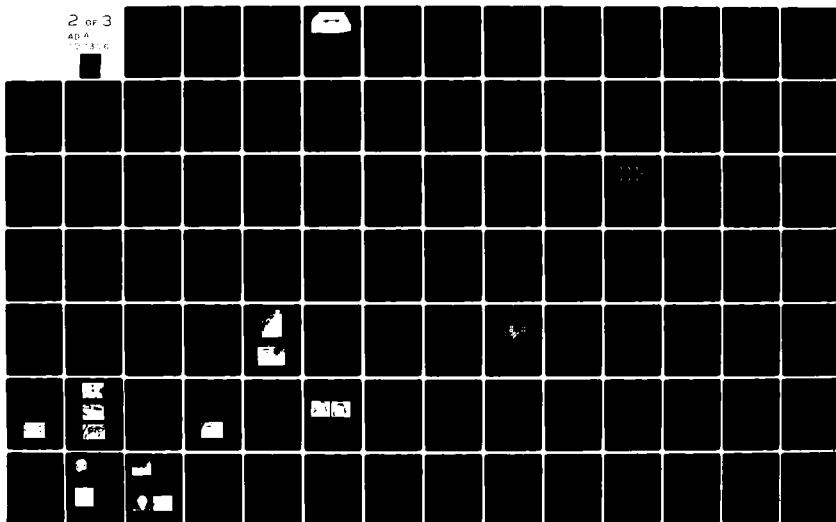
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2.0

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1.4

1.6

McRae COPY RESOLUTION TEST CHART
1963-A

The CRT display is capable of displaying far more characters per unit area than any other display technology that one would seriously consider. When stroke writing is used, the CRT display has higher resolution than anything short of paint. It does not require a separate device for each character space on a line and a wide variety of character shapes can be generated. It is readable in direct sunlight thanks to advances in narrow-band phosphors and optical bandpass filters. Dimming is uniform from intensities required for bright sunlight conditions to the night vision goggle range. CRT life is long if conservative design practices are used. These include keeping the anode beam current to low levels and utilizing ruggedized electron gun assemblies. It has no viewing angle restrictions to preclude its use in any cockpit location. Various color phosphors are available for use in different applications. These include red for night adaptation and green for better day visibility.

On the other side of the ledger, the use of a CRT in a CDU unavoidably creates a certain amount of overhead so far as volume, weight, and complexity are concerned. From a cost point of view, the CRT starts looking attractive above roughly 3 lines of 20 numeric characters, fewer if alphanumeric characters are used. The military services have experienced poor reliability with some equipments using CRT's, but this is usually due to inadequate design and procurement practices rather than technological barriers. Rockwell has experienced CRT MTBF's in excess of 15,000 hours in a half-million flight hours for commercial transport service.

Considering the display media alternatives, all have weaknesses. LED's absolutely flunk the sunlight test unless the drive power is increased to unacceptable levels. Plasma cannot be dimmed to low light levels without unacceptable flicker. Liquid crystal (LCD) technology is not sufficiently mature for airborne application. Problems of incandescent include segment dropout with dimming, heat, and filament notching resulting in lower reliability when driven at high dc voltages.

Front Panel Controls

The primary consideration in the design of front panel controls and control sequences is the reduction of crew workload. It is to this end that control requirements are generated. The process for performing this task includes the following issues:

1. What functions are to be performed?
2. What is the sequence of activities associated with these functions and how should they be grouped?
3. What priority requirements, such as emergency controls, exist?
4. Under what conditions (mission phase, aircraft dynamics, cockpit placement, etc) must control inputs be made?

Consideration of these issues will lead to operational requirements for the necessary CDU controls and control sequences. For example, in figure 1 the functions performed by three of the IACS units are shown. Even with a list of controlled functions for only three of the seven units in the system, it is obvious that:

1. Some sort of multifunction switching scheme must be implemented (ie, not all functions can be represented by a dedicated switch).
2. The state of all functions cannot be displayed simultaneously.

In reference to the first observation, a technique used in earlier Rockwell CDU's was to place a column of pushbuttons (called line select keys) on either side of the display. The function which the key performs was defined by a label presented on the display adjacent to the key. This technique is particularly appropriate for a standard CDU because the particular aircraft application software determines the functions which the keys will perform. With no hardware changes the keys can perform different functions for different aircraft applications.

The second observation implies the need for display overlay or paging techniques. Basically, two types of paging schemes can be used: equipment oriented or mission oriented. The equipment oriented scheme defines a separate display page(s) for each piece of controlled equipment. The mission oriented scheme defines display page formats on the basis of information requirements for each mission segment. An example of a typical page in an equipment oriented scheme is shown in figure 2. This example is a control page for an APX-100 IFF as implemented for IACS. The line keys on either side of the display allow the operator to enable, disable or change IFF modes and change IFF mode code data. All keyboard entries first appear in the scratch pad (brackets in the lower portion of the display). Entered information is then transferred from the scratch pad to an active line by pressing the appropriate line key. An example of typical pages in a mission oriented scheme (also implemented in IACS) is shown in figure 3. This example shows a set of control functions from different equipment, grouped to perform preflight avionics tests. Mission and equipment oriented schemes can be mixed to enhance performance as long as it is done in a way that is not confusing to the operator.

The combination of multifunction switching and display paging creates almost limitless capabilities for flexible control of remote avionics. The utilization of software labeled keys, however, does not totally solve the problem of the definition of a standard control panel. It does, however, go a long way towards that goal since much of the labeling of modes and data entry is done in software. The remainder of the front panel controls, in Rockwell's experience, has been fairly fluid. Each application has required a different front panel. Examples of the various front panels Rockwell has or will have in production are shown in figure 4. The approach to reduce the problems associated with these front panel changes has been to keep the line select keys the same in each application and also make design changes easier to accomplish in the remainder of the panel.

In the electrical design, a matrix has been included which will encode up to 64 keys. The electrical design also includes provision for two rotary switches with up to 20 switch positions, CRT brightness control, a BIT indicator, and three toggle switches. Any combination of these controls may be put into the mechanical design of a front panel with no electrical design changes. This has resulted in quick development turnaround for new CDU applications and development cost savings.

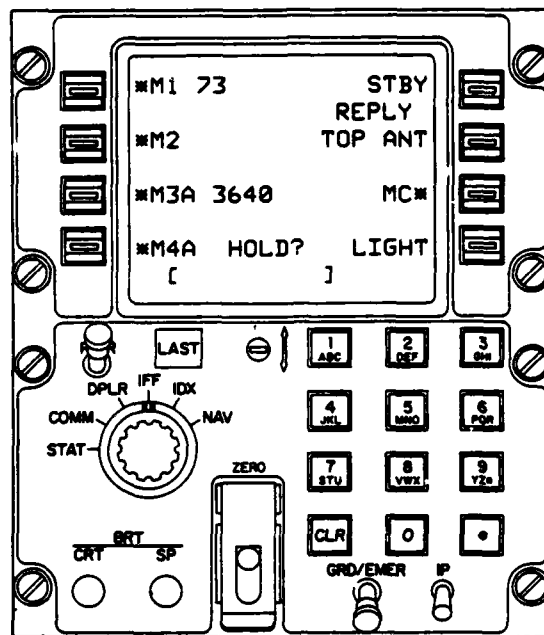
<u>EQUIPMENT</u>	<u>FUNCTION</u>	<u>STATES</u>
UHF (ARC-164)	Power	Off, On
	Mode	T/R, T/R + G
	Bandwidth	Wide, Narrow
	Tone Xmit	On, Off
	Channel	1-10, Manual
	Frequency	225,000 - 399,975 MHz
	Squelch	On, Off
	Preset Entry	1-10
VHF-FM (ARC-114)	Power	On, Off
	Mode	T/R, T/R + G, Retran, Homing
	Channel	1-10, Manual
	Frequency	30.00 - 75.95 MHz
	Squelch	Off, Noise, Tone
	Preset Entry	1-10
	Test	On, Off
IFF (APX-100)	Power	On, Off
	Status	Normal, Standby, Emergency
	Mode 1	On, Off
	Mode 1 code	00-73 (Octal)
	Mode 2	On, Off
	Mode 3/A	On, Off
	Mode 3A code	0000-7777 (Octal)
	Mode C	On, Off
	Mode 4	Off, 4A, 4B
	Antenna	Top, Bottom, Both
	M4 Annunciation	Off, Light, Audio + Light
	Identify Position	Initiate (Momentary)
	Mode 1 Test	On, Off
	Mode 2 Test	On, Off
	Mode 3/A Test	On, Off
	Mode C Test	On, Off
	Mode 4 Test	On, Off
	Radiation Test	On, Off
	Zeroize	Initiate (Momentary)
	Mode 4 Code Hold	Initiate (Momentary)

Figure 1. Control Functions for UHF, VHF, and IFF.

Form and Fit

The width of the CDU was specified to be in accordance with US Military design standard MS25212 (5.75 in (146.05 mm) width, 8.0 in (203.2 mm) depth including cable bend). The actual unit depth was set at 6.5 in (165.1 mm) excluding connectors. The MS25212 size requirements were specified by the IACS and A-10 CDU procurement specification. In addition, a review of control/display units on various military aircraft indicated that this width and depth was acceptable in the high majority of cases. When comparing this desired depth to the display size required it was found that a CRT with a 70 degree deflection angle would fit. This deflection angle was low enough to produce a CDU of reasonable power consumption. In order to determine optimum CDU height a number of additional considerations were necessary. The Army IACS specification allowed for a maximum CDU height of 10 in (25.4 cm). Obviously, to maximize the usefulness of the CDU over all aircraft types from fighters to transports the smallest height possible was desirable. Since display capacity and media had been tentatively determined CDU height was now dependent largely on the type of additional controls needed. A high-g fighter generally requires controls such as rotary knobs which have sufficient tactile feedback to be operated in a heads-up mode. The requirements of a transport aircraft, on the other hand, are quite different and a full alpha keyboard may be desirable. Since a full alpha keyboard requires more panel space than the other control configurations conceived for the CDU, the panel size was based on it. A 6 by 5 key matrix was needed to accomplish the alpha function so the necessary space for keys and sufficient interkey spacing for gloved operation was provided. When combining this with CRT size and assembly requirements the resultant CDU height was fixed at 7.125 in (180.97 mm).

The resultant "standard" front panel design is shown in figure 5. It utilizes 8 lines each with 19 characters. Data may be entered or modes controlled on lines 1, 3, 5, and 7 due to the positioning of the line select keys. Lines 2, 4, and 6 are used as label lines or for display data which the pilot does not modify. Line 8 is always utilized as a scratch pad where data is entered and verified by the pilot before entry into the system via the line select keys. No keyboard configuration is shown for the "standard" front panel. This is because our experience in the development of a number of systems is that the front panel usually changes in some way to solve a system problem. This is not to say that with additional effort an unchanging truly standard front panel could not be developed but it has thus far been Rockwell's approach to allow for easily accomplished front panel design changes for individual applications.



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Figure 2. IFF Control Page.

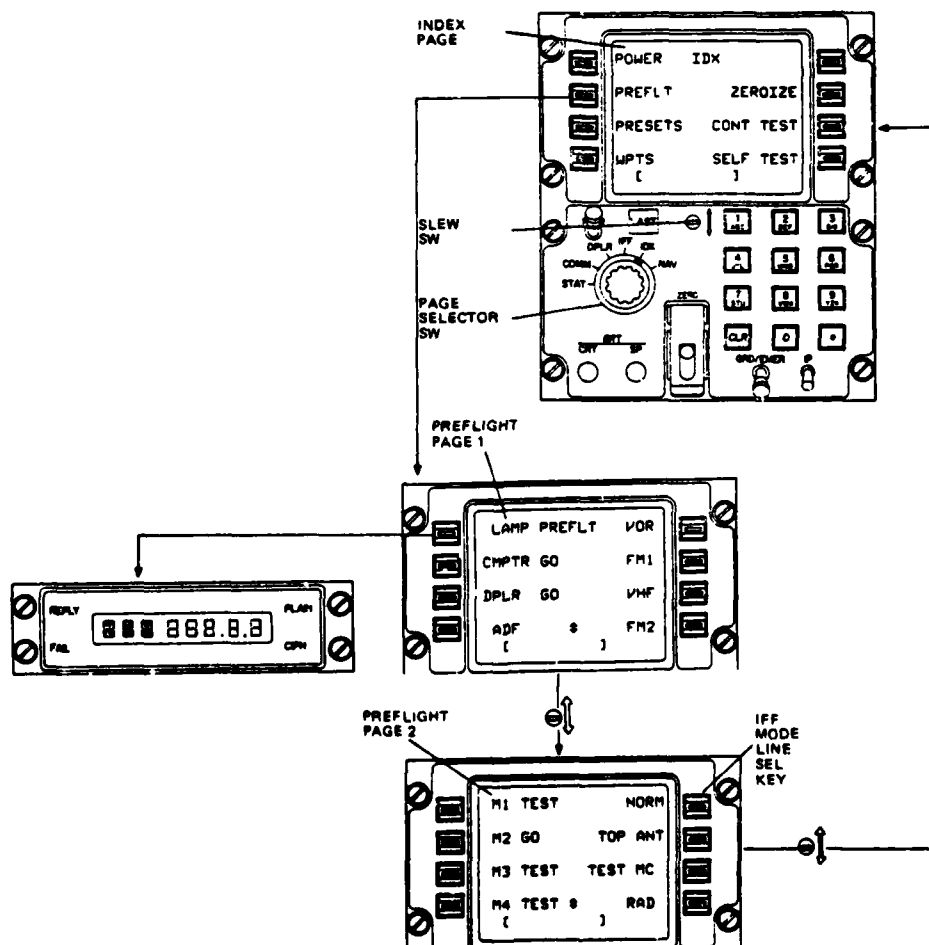


Figure 3. Preflight Test.



Figure 4. Various CDU's Utilizing the Standard Design.

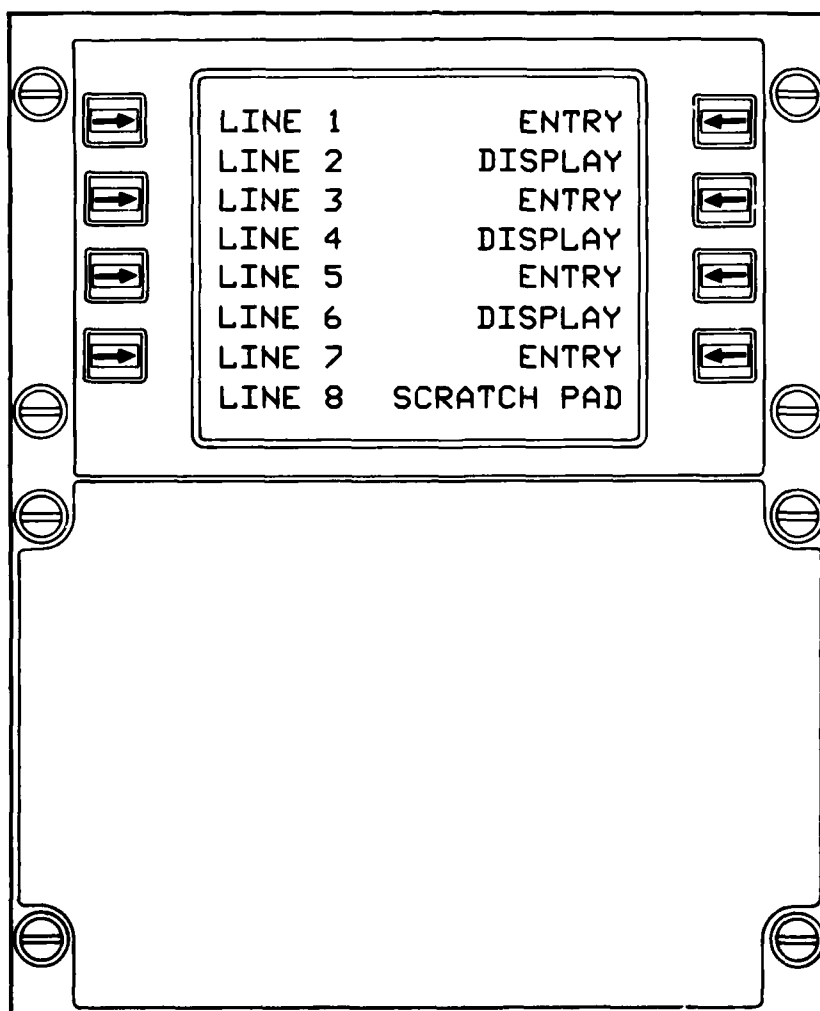


Figure 5. Rockwell "Standard" CDU Front Panel.

Processing

During electrical design and partitioning it was apparent that some means of reducing the amount of electrical hardware was needed. If the hardware could not be reduced it would be necessary to put nonsimilar functions into one module, to put circuitry in the usually inaccessible areas around the CRT, or to increase CDU size. The first two alternatives would cause problems from a built-in-test and maintainability point of view and the third was somewhat unacceptable from a "standardization" point of view.

In order to reduce the amount of hardware, various types of high-speed processors and processor slices were considered as programmable devices which could be used to "convert" hardware into software. The final solution included a 125 nanosecond clock cycle, programmable controller which was composed entirely of inexpensive low power Shottky LSI devices. This controller was used to remove most of the control logic from the 1553 interface, the keyboard encoder, and character generator. It also facilitated built-in-test since control of the CDU was now centralized. For maintenance and logistics requirements, the CDU was partitioned and constructed with common functions separated into separate cards or modules. Extensive monitoring of the modules was included to optimize BIT performance. The controller was utilized to provide as much error checking as possible. Monitor lines from each card or module are sensed by the controller and the results displayed on the CRT if possible.

The Rockwell concept of a "standard" CDU evolved further when it was chosen as the CDU to control the Standard Inertial Navigation Unit (INU) aboard the A-10 aircraft. The A-10 requirements dictated that the CDU could no longer be "dumb" but needed general purpose processing power internal to the CDU to perform INU control, data processing, display page formatting, and other aircraft related functions. Because of the modularity of the existing IACS hardware design it was a rather minor modification to add a 8085 microprocessor and associated memory. This was done by removing Input/Output circuitry that was required for IACS but not required for the A-10 CDU and putting the remainder of the circuitry on another card which had spare space. The resulting unused card slot was used to add a microprocessor card. The microprocessor utilizes ultraviolet erasable EPROM's for program memory which may be programmed without removing them from the printed circuit card. EPROM's were used in order to allow maximum versatility in changing the CDU program. In regard to standardization, it is therefore possible to procure the CDU without software installed and then program its EPROM's at the maintenance depot to perform the control/display function desired. A basic CDU could then be purchased for a variety of aircraft and programmed by the user to perform the desired aircraft functions. The software language utilized is PLM which is easy to use and is very easily supportable on a low cost INTEL Corporation MDS (Microprocessor Development System).

The addition of the processor also provided for additional computation power to further enhance built-in-test performance especially for intermediate (I) level (maintenance to the card or module). During normal CDU operation, the processor continuously monitors lines from each module and a BIT indicator is set if a failure is detected.

During off-aircraft intermediate level testing, a simple test fixture which contains no active components is used to tie CDU outputs to CDU inputs and MIL-STD-1553 multiplex bus A to bus B. Intermediate level test is initiated by grounding a pin at the rear connector. The microprocessor then continuously sets CDU outputs and reads the resulting wrapped-around inputs. MIL-STD-1553 traffic is initiated on one bus and the data coming back on the other bus is checked for accuracy.

If the CDU has failed in such a way as to still allow the displaying of a page the following test data is displayed during intermediate level testing:

1. An indication of the failed module
2. The state of all front panel controls
3. The entire symbol set

If no module is listed as failed, the last two displays allow maintenance personnel to check the front panel controls and display. A large part of the CDU circuitry is related to the CRT display and if a failure occurs in this area the CRT will be inactive and cannot be used to indicate where the problem lies. In this case the built-in-test (BIT) indicator is used along with a front panel rotary switch to isolate to the failed card or module, provided of course that the power supply has not failed. The BIT indicator is a device which normally indicates whether or not the box has failed by displaying a latched ball which is either black or white. In this case it is also utilized as a readout device since the CRT is blank. The rotary switch is first switched to a position which causes the BIT indicator to set to prove to the operator that the BIT indicator has not failed. The rotary switch is then rotated and the state of the BIT indicator read for each position of the switch. The resultant data is used to define which card or module has failed. These functions allow the maintenance personnel to isolate to a card or module in the high majority of cases without utilizing so much as a test probe. This keeps the maintenance problems associated with test equipment induced failures to a minimum and allows the use of low skill level maintenance personnel.

The processor addition has also allowed the CDU to act as MIL-STD-1553 multiplex bus controller, a function the CDU will perform in a backup mode on the US Army SEMA aircraft. Normally a given multiplex bus system has a master bus controller which initiates and monitors all traffic on the bus. In addition, a backup bus controller is needed for redundancy purposes. In many systems a separate unit with the associated penalties must be added to accomplish one of these bus control functions since most MIL-STD-1553 avionics equipment does not have bus control capability. Including the bus control function in the CDU gives the aircraft designer more flexibility when deciding upon the avionic complement.

SUMMARY OF REMAINING ACTIVITY

The drivers for Rockwell to "standardize" its CDU product line have been to minimize development time and nonrecurring costs for each application. Associated with these drivers are logistics issues which are of major concern to the military. The two primary issues which have thus far prohibited a truly standard CDU development are processing and control panel configuration.

It would seem that the issue of processing and its associated nonstandard software could be resolved by requiring no aircraft specific processing functions be included. While this is adequate for some applications, these are also applications where such a decision would dramatically increase aircraft life-cycle costs; and reduce reliability and mission effectiveness. A good example of this is the A-10 aircraft. The A-10 has no mission computer. The Standard Inertial Navigation Unit supplies information to the multiplex bus which is independent of the implemented CDU. Without processing capability within the CDU, an additional processor would be required to take inertial information and format it for the "dumb" control/display. The impact of such an implementation is additional hardware causing higher aircraft cost, additional maintenance, and reduced aircraft availability. The issue of processing within the CDU ultimately hinges on the acceptance of application unique software. If hardware commonality is sufficient, then one can enjoy the flexibility and growth associated with a "smart" CDU. If it is not, then the application of the CDU must be limited to those systems which have sufficient processing capability to assimilate the control/display functions. One additional approach the military could take is to procure a standard CDU which has no software installed. The CDU ultraviolet erasable programmable memory card could then be programmed at the maintenance depot with program tapes purchased from a supplier or developed by the military for the desired application.

Standardizing the control configuration is an even more difficult issue. Our experience has been that each application requires a different control configuration. If standardizing for one particular category of aircraft, such as transport, it is possible that a standard pushbutton matrix could be developed. The difference in flight regimes across categories, however, considerably reduces the probability that one control configuration will be acceptable to all users. Rather than try to develop a standard control panel Rockwell has developed a modular design which lends itself to modification for particular applications. What advantages this would have for the military needs further study.

DEVELOPMENT OF A MINIATURISED DIGITAL THRUST DEMAND UNIT

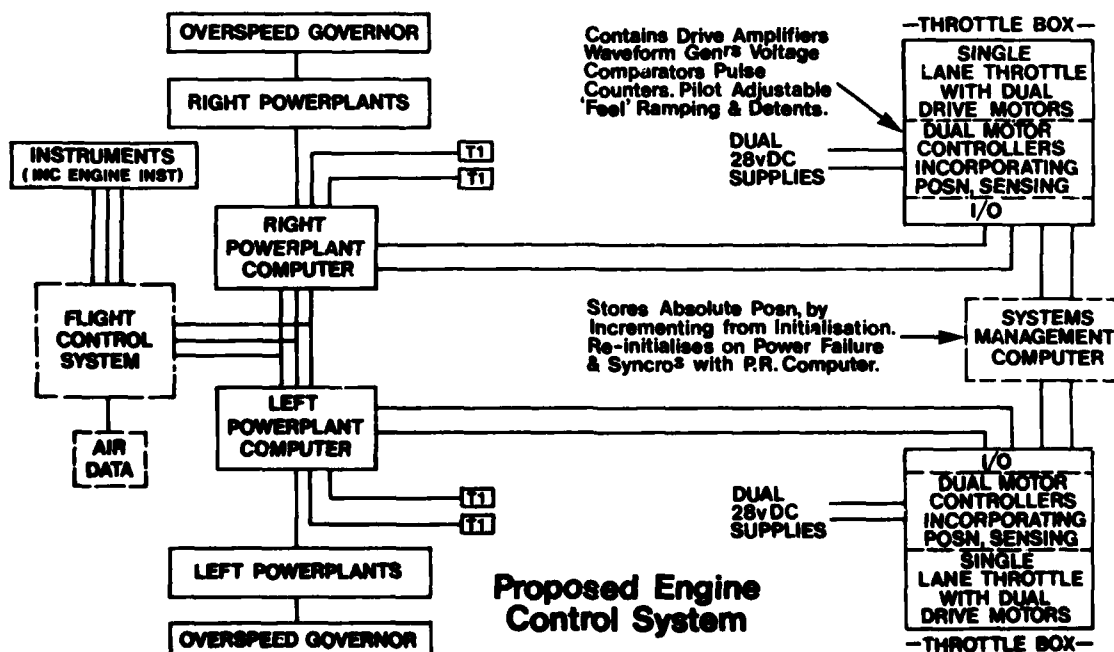
by
 Arthur Kaye
 Advanced Control Systems Group
 MILITARY AIRCRAFT DIVISION
 British Aerospace
 Warton Aerodrome
 Preston
 U.K.

SUMMARY

Control and display areas in proposed air superiority aircraft have been significantly reduced, necessitating multi-function displays and controls where possible and the miniaturisation of dedicated controls. The paper describes a possible future engine control system and the development of a compatible thrust demand unit. Present generation analogue units are analysed in order to produce design guidelines for the new line replaceable units (L.R.U.s). The elimination of the motion conversion chain, linear to angular, angular to linear is shown to afford significant savings in weight and volume. Angular motion and compliant force throttles, whilst creating maximum space saving, are shown to be ergonomically inferior to a linear input. An explanation of the operating principles of the linear stepper motor chosen as the auto-pilot prime mover is given with both the inherent advantages and disadvantages used to good effect in the overall design. Digital position encoding completes the design of the prototype unit and the results to date of the testing of this unit are given with recommendations for the design of a production unit.

Cockpit profiles for air superiority aircraft are constantly striving to increase the pilots arc of vision. This can be achieved by lowering the canopy sills, but a greater pro-rata increase in arc of vision is achieved by reduction of cockpit width. Control consoles situated on each side of the pilot immediately become targets for reduction by the introduction of multi-function controls or the miniaturisation of dedicated controls. One such control, normally occupying the left hand console on single seat aircraft, is the throttle box. These units have historically been directly connected via mechanical linkage to the powerplant, although more recently analogue fly-by-wire systems have been adopted.

FIG. 1 - TYPE OF CONTROL SYSTEM



Powerplant control systems envisaged for the next generation of aircraft include those using digital techniques. Investigations are being conducted by various powerplant manufacturers into the possibility of integrating the powerplant and its digital control unit. This effectively reduces the engine/airframe interface to fuel supply lines, and introduces a digital highway which will probably be triplex, electrical power supplies and possibly a high speed dedicated digital link from the cockpit thrust demand unit. More importantly, the power plant is tending to become line replaceable without the requirement for recalibration after its replacement.

Auto pilot thrust demands will be signalled directly to the engine mounted control unit from the Flight Control System computer via the triplex digital highway. To afford tactile feed-back to the pilot the throttle handles will be signalled to synchronise position with the power plant control unit via the dedicated digital high speed link. To enhance manoeuvrability in twin-engined aircraft a degree of asymmetric engine thrust may be demanded by flight control system. This will occur about the datum set by the pilot in the manual mode of operation. Tactile feed-back will be signalled in an identical manner to that in the auto-pilot mode.

Analysis of the present generation of throttle boxes produced the conclusion that many were derivatives of the original mechanically-orientated design concepts with position pick-offs and auto pilot drive units appearing to be added as an after-thought. In the majority of cases, the handles had been pivoted about a fulcrum to create mechanical advantage, originally for the direct operation of fuel valves on the engine, but later also for position pick-offs and auto-pilot drives. The original pilot input, essentially linear motion was converted to angular motion, back to linear motion and finally to angular motion once again. It was decided that the use of a motion conversion chain such as this demanded a prohibitive amount of space and that for fly-by-wire aircraft it was no longer required. Prior to the production of a design specification, three concepts of pilot input were investigated, purely rotary, compliant force and purely linear. Whilst the purely rotary and compliant force throttles offered the greatest savings in space and weight, they proved ergonomically inferior to the purely linear concept in terms of either tactile feed-back or built-in-feel. On both concepts it was found impossible to determine a rough estimate of percentage thrust by feel alone. The production of tactile feed-back in the auto pilot mode not only increased drive complexity but also under panel space requirements. A decision was made to continue the design of the purely linear thrust demand unit which should meet the following design criteria.

FIG. 2 -

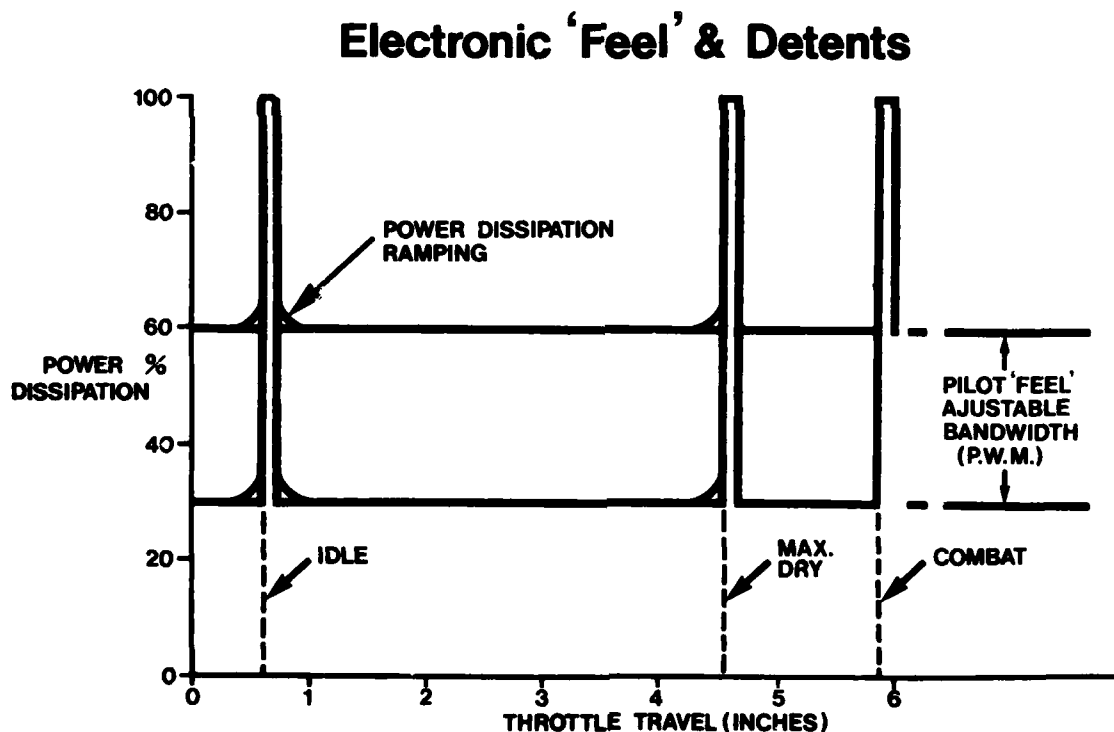
Design Criteria

Volume		
Length 200 mm	(Travel 200mm)	(11 inches)
Depth 100 mm		(4 -)
Width 60 mm		(2½ -)
Weight		
Approximately 5 Kgs		(11 lbs)
Interface		
Digital, MIL STD 1553B Compatible.		
Feedback		
Tactile Feedback to Handle when Operating in Auto Pilot Mode.		
Ergonomic Interface		
The Module to have Pilot Adjustable Build in "Feel."		
Interchangeability		
The Unit must be Adaptable for any Aircraft, both Civil and Military, which uses Fly-by-Wire Techniques for Power Unit Control.		
There must be No Requirement for Calibration on Replacement.		
Positioning		
The Unit must be Capable of Signalling Thrust Demands in both Manual and Auto Pilot Modes. There shall be no Overshoot or Oscillation when Operating in Auto Pilot Mode.		
Detents		
There shall be Finite Detents in Throttle Movement for Max. dry, Reheat and Combat Reheat.		
Speed of Operation		
Travel between Min. and Max. Throttle Settings to be Completed in 1 Sec.		

The decision having been taken to proceed with a purely linear concept, a design was produced using a linear force motor which, whilst meeting the design criteria, had certain fundamental limitations. Prior to the production of a prototype unit the design of the motor controller appeared to become over-complicated. As no overshoot or oscillation was allowed, critical damping of the motor slider was essential but unfortunately the load on the motor was infinitely variable. Motor loading is derived from three separate sources; the first is the pilot adjustable frictional load which provides built-in-feel and also the finite holding torque when the motor is de-energised. The second source is the 'g' force imposed on the motor slider during aircraft manoeuvre and the third source is applied by the pilot's hand resting on the handle. Control systems postulated for future aircraft appear to be digital in nature and as the force motor is not inherently a digital device, further signal conditioning was required. Added to this the machining of mechanical detents for the idle, max. dry and reheat positions contributed to the manufacturing costs and increased motor size.

Whilst control systems engineers would not find these problems too difficult to surmount, it was felt that a more suitable prime mover might be found. An investigation was conducted into the possible benefits of using a linear stepper motor as the auto-pilot prime mover. An obvious advantage was the inherent digital nature of the stepper motor making the interface with the control system relatively simple. As the investigation progressed, other advantages became apparent. Closed loop control of the stepping rate with speed ramping for acceleration/deceleration could eliminate possible overshoot and oscillation. Pulse width modulation techniques could be used to minimise power dissipation when the machine was stationary and yet a holding torque would be provided, thus eliminating the need for a frictional load. Elimination of the mechanical detents for the idle, max. dry and reheat positions could be achieved by increasing the motor power dissipation to 100% at these specified positions.

FIG. 3 - DIAGRAM: BUILT-IN-FEEL & ELECTRONIC DETENTS



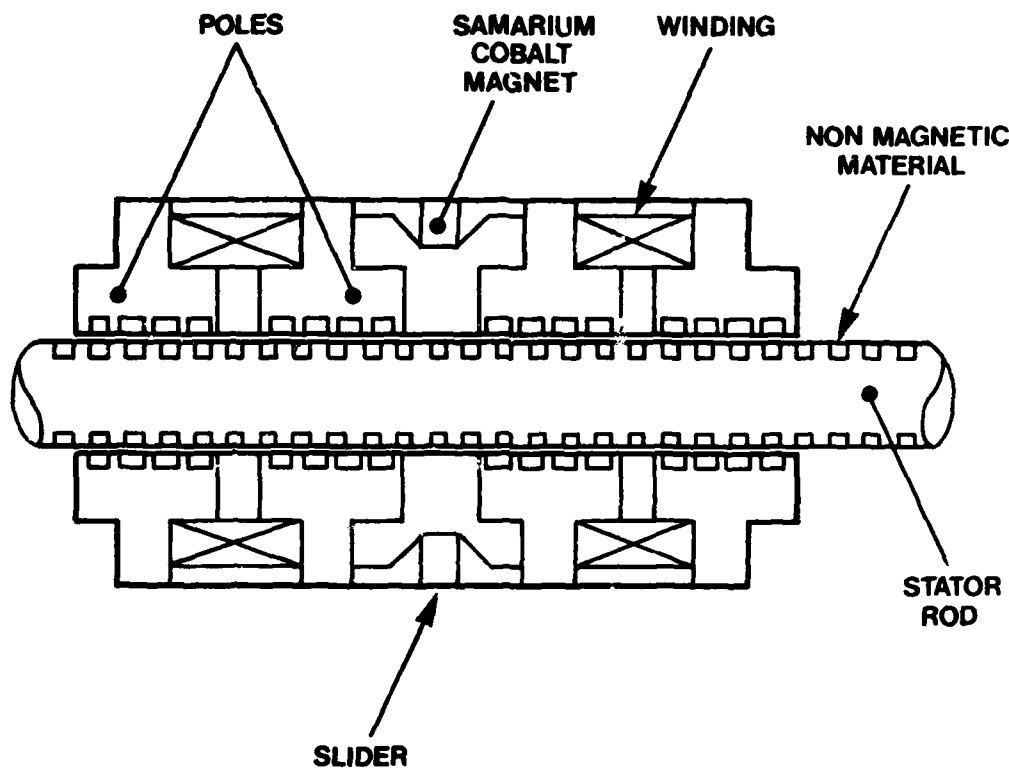
All of these control inputs could be engineered in the software program, thus eliminating the need for the costly machining exercise.

The advantages realised in the use of a stepper motor were conclusive enough for a decision to be made to produce a twin lane prototype unit and an 'INLAND MOTOR' type O806A was chosen as the primer mover.

The linear stepper motor has two basic parts; a solid rod of circular cross section and a cylindrical slider supported on the rod with bush type bearings. Either component may be fixed, thus allowing the other to carry out the stepping function. The slider consists of a non-magnetic cylinder fitted with ring shaped inserts which carry the phase windings, slider bushes and Samarium Cobalt rare earth magnet whose magnetic axis is parallel to the direction of motion. Both the pole pieces and the rod on which it slides have toothed faces such that when the teeth of one pole piece are co-incident with those of the stator rod, the teeth on the other pole piece are 180° out of phase. The teeth on both the pole pieces and the stator rod are cut in the form of a helix, those on the stator rod being filled with a non-magnetic material prior to hard chrome plating to afford a reasonable bearing surface for the slider bush bearing.

FIG. 4

Cross Section of Linear Stepper Motor

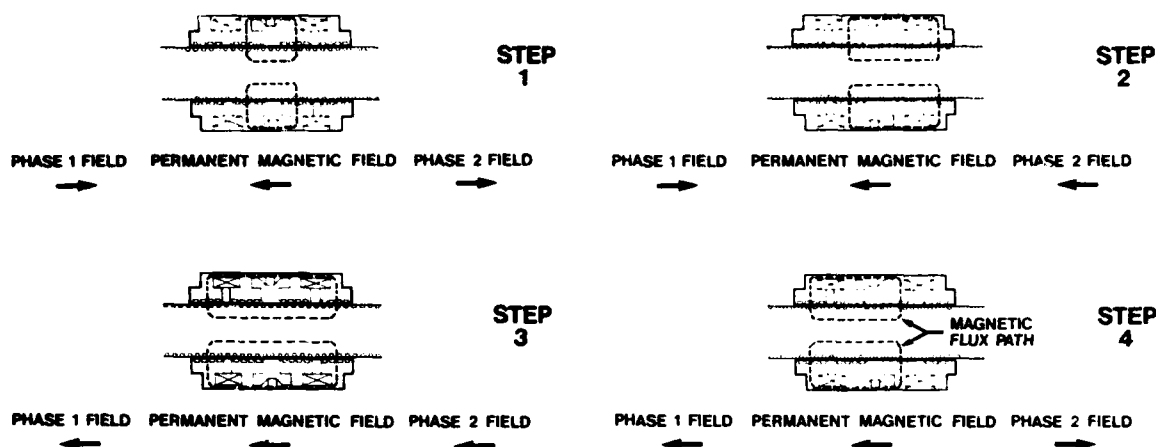


The motor has four distinct electro-magnetic states with minimum energy positions associated with each. The four states are produced by four combinations of current flow in the two phase windings which effectively changes the magnetic flux path produced by the permanent magnet.

A direct current of constant magnitude is applied to each phase winding and this produces a balanced magnetic state in the slider due to the inter-action of the permanent and electro magnetic fields. This causes the slider to move to a position in which slider and stator teeth are aligned with minimum magnetic reluctance for that particular field configuration. Reversal of the current in any particular field winding will change the field configuration, rebalance will occur when the slider has moved to the next position of minimum magnetic reluctance (.025" step). The next step is taken when the second phase winding current is reversed. A change of direction can be achieved by re-reversal of the current in the last phase winding to be changed.

FIG. 5 - 4 MAGNETIC STATES OF THE MOTOR

Operating Principles



Providing that the motor is not held under mechanical stall conditions, it is capable of stepping at rates up to 150 steps/sec under open loop control. However, in the thrust demand unit application, the load is continually varying and it is possible for the pilot to induce mechanical stall conditions by increasing 'g' forces or by holding the levers. With open loop control this would cause the motor to go unstable and possibly step in the wrong direction; closed loop control is therefore essential to the application. Position sensing is not only required to close the control loop, but is also required to determine acceleration/deceleration ramping during auto-pilot mode and also for thrust demand modulation in both auto-pilot and manual modes.

Many forms of position encoding were investigated with the ideal system being defined as linear absolute. This conformed to the original design concept of not requiring a motion conversion chain from linear to angular, thus retaining minimum unit volume. However, in the timescale available for the production of a prototype evaluation unit, it was found impossible to obtain such a device in digital form and it was therefore decided to concede to the use of a rotary absolute encoder driven by a scroll shaft. Manufacture was completed in January 1981 of a simplex twin lane unit incorporating a simple drive motor per lane with a single position encoder driven by each motor and with removable mechanical detents.

Whilst manufacture of the prototype unit was progressing, the concept of the production unit began to emerge.

It was envisaged that the production unit, whilst meeting the original design criteria, would also be a single lane duplex unit with the possibility of a reduction in travel to 6 inches. This modular approach would allow the unit to be fitted to any fly-by-wire aircraft of single or multi engine configuration, civil or military, manufactured by any aerospace company. The unit would incorporate two drive motors which would be used to drive and support the throttle handles.

From investigations carried out by the motor manufacturers into closed loop control, it has been proved that because of the change in magnetic reluctance, which occurs during relative motion between stator rod and slider, a consequent delay is introduced to the natural exponential build up of the voltage waveform.

FIG. 6 - BASIC CLOSED LOOP CONTROL

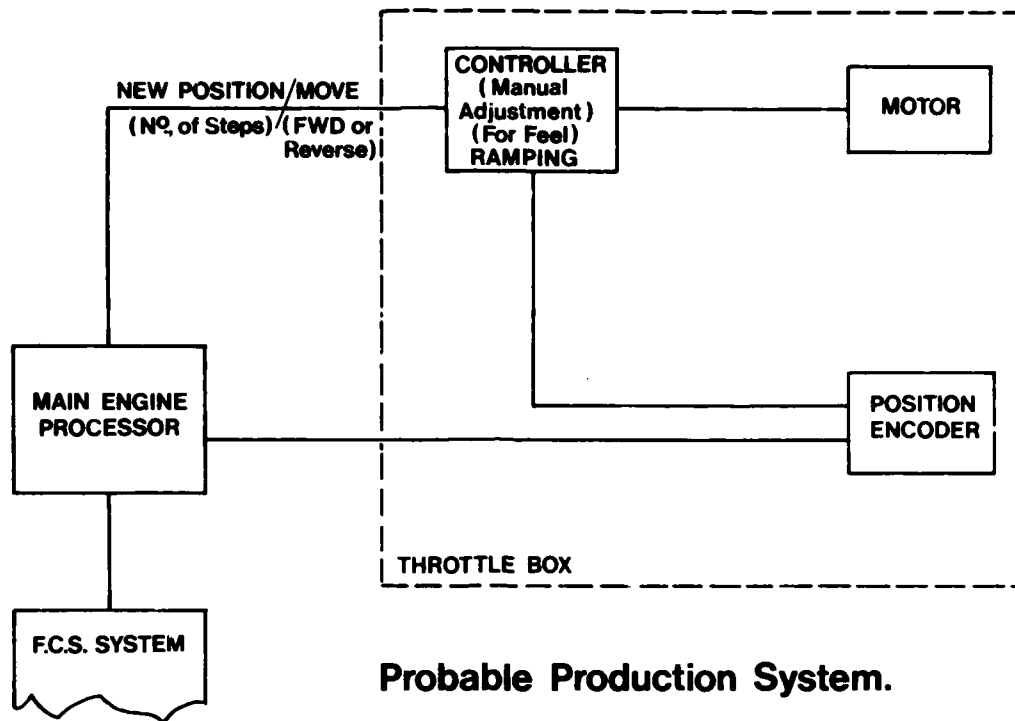
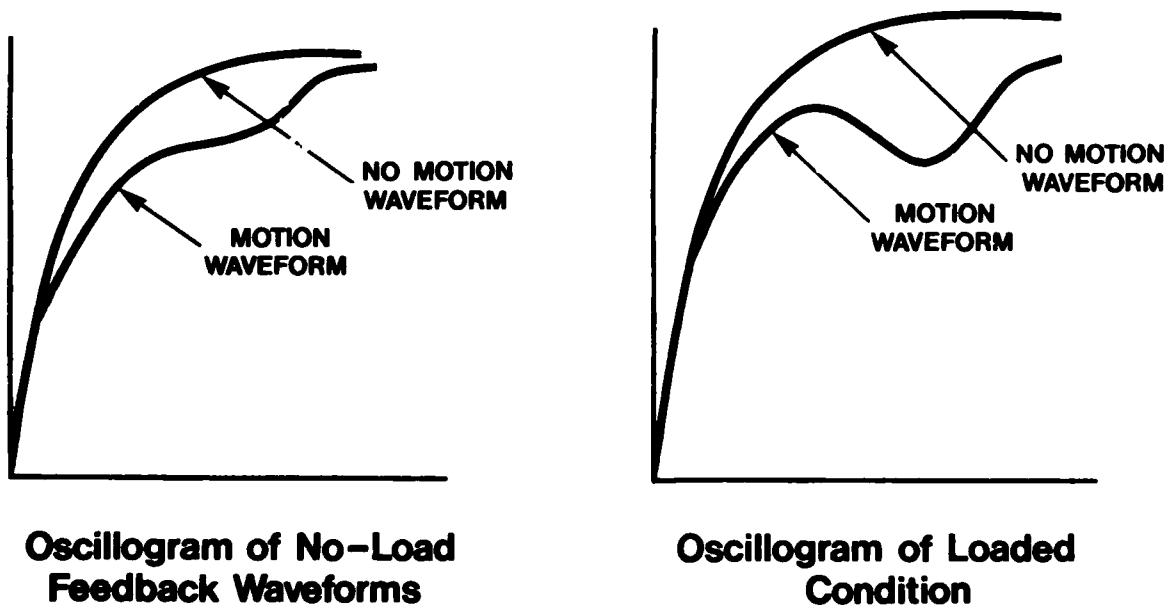


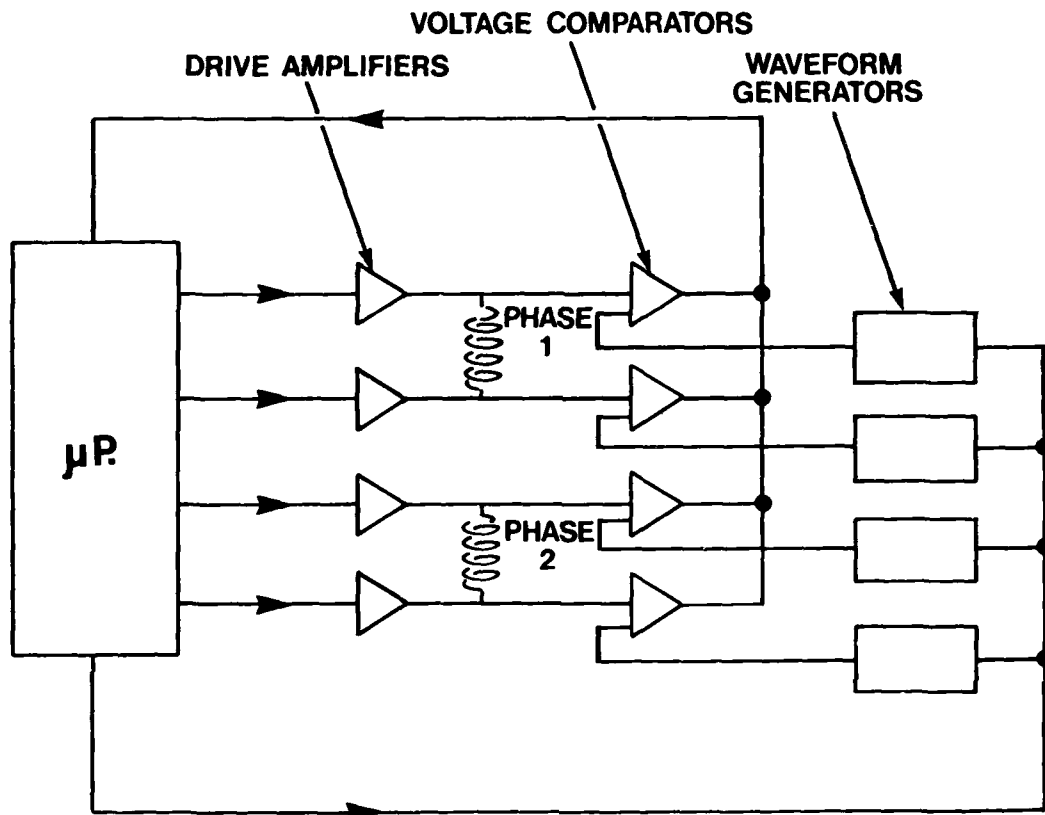
FIG. 7 - WAVEFORMS



By signalling a voltage generator to output the no motion waveform at the same time as signalling a step to be taken, a comparison of the two will determine whether a physical step has been taken. The same signal will be repeated until a step is achieved, success will induce the next step in the sequence to be signalled.

FIG. 8

Closed Loop Control



In the manual mode, the motors will continue to be energised to a percentage of full load (see Fig. 3). In this mode it is hoped to sense some physical movement by monitoring the phase windings for induced voltages due to the changes in magnetic reluctance. Should there be a failure to sense movement in this manner, then Hall Effect sensors would be used, fixed to the slider, to sense the teeth of the stator rod. Once movement under manual operation has been successfully sensed, it is believed that by sensing two separate sources disposed 180° out of phase with each other, it would be possible to sense not only movement but also the direction of the movement.

Having defined the production unit in this manner, the next step was to draw up a test plan to be carried out on the prototype unit which could prove the production concept. Testing was therefore to be carried out in accordance with the list given in Fig. 9.

When a modular unit, such as that proposed as a production unit, is installed in an aircraft and indeed each time the aircraft is subsequently powered up, the datum is set in the powerplant computer with throttles in the "locked off" position. From this point, duplex memory locations in the powerplant control computer would be incremented or decremented with changes in throttle position. Should a double fault situation occur in the motor power supplies engine thrust modulation will be frozen and on resumption of any one supply, re-synchronisation will occur by driving the throttle handles down to the idle position to reset the datum and then driving up to the demand frozen in the engine control computer.

The advantages of the use of the new thrust demand unit are therefore reduced console space requirement, reduced weight, direct digital interface and the modular approach allows replacement of a single lane unit without the need for recalibration.

To make the unit truly universal and suitable for any type of aircraft, the throttle handles would be detailed separately. Some would require switches for various military applications, such as radar ranging, armaments, communications; other handles for commercial applications may require no switches at all.

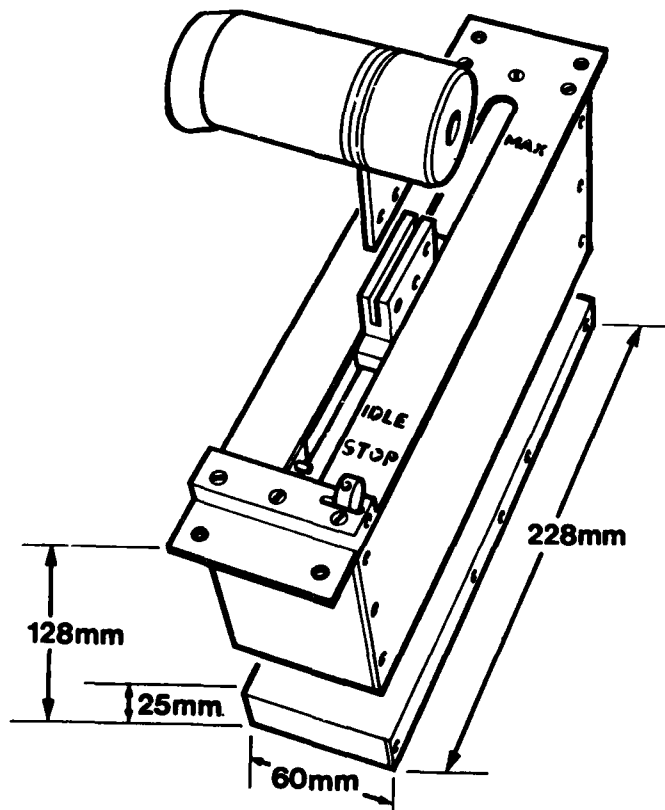
FIG. 9 - TEST PLAN

Test Plan

1. Determination of Maximum Driving Torque.
2. Determination of Maximum Detent Torque.
3. Voltage Sensing: Motion & No Motion Waveforms.
4. Determination of Magnetic Field Strength on Each End of Stator Rod. (Energised & De-Energised States)
5. Determination of Total Travel Time.
6. Investigate Voltage Pulse Sensing for Manual Operation Position Encoding & Direction Sensing.
7. Stray Magnetic Field - Compass Safe Distance.

FIG. 10 -

Production single module.



A number of mock-up models of the production units have been manufactured and will be fitted to various cockpit layouts developed for future aircraft. The modularity of the design allows for easy installation and removal of the units in single and multi engine cockpit layouts. The overall dimensions of a single lane unit is 268 mm including mounting flanges 65 mm wide and 128 mm deep which includes the duplex electronics package. Handles have been detailed separately and include a method of selecting thrust reverse but no provision has yet been made for the inclusion of switches.

The unit is subject to two British patent applications numbers 800846 and 8031102 and applications covering Sweden, Spain, Italy, France, Germany, Holland, U.S.A. and Canada have also been made.

RESULTS

Bearings fitted to the two prototype drive motors were manufactured in "ENVEX" polymer. This material is self lubricating and has excellent positive temperature characteristics. During transportation from the manufacturer however they were subject to a temperature of approx. -50°C for some 7 hours. It is believed that this caused the subsequent premature failure of all the bearings after approximately 15 minutes running. Replacements manufactured in the more conventional phosphor-bronze were fitted and 5 hours continuous running produced no significant wear.

Tests were carried out to determine the holding torque of the motor both in the energised and de-energised states and the results were as follows.

de-energised	17 ounces	(.45 Kg)
energised	12 pounds	(5.4 Kg)

Waveform sensing and voltage pulse sensing checks were carried out using an oscilloscope and whilst voltage pulsesensing was quite significant at an operating speed of 200 steps/second at speeds below 40 steps/sec voltage amplitude was reduced to the point where it entered the area of permissible exported noise as defined in aircraft specifications.

CONCLUSIONS

Although cockpit simulators work has been delayed prototype testing is expected to be completed by September 1981. The original space envelope is still considered valid and therefore production standard drawing is due to commence during March 1981. Due to the results obtained from testing waveforms and voltage pulse sensing it has been decided that separate absolute position sensing will be included in production units. As drive motor windings will not be used to sense position a single drive motor will be used although electronic modules will still be duplex on separate plug-in cards. Circuits incorporated in the electronic modules will be those for motor drive, position sensing, discrete to digital conversion, serial bi directional I/O's, closed loop feedback for drive motors, electronic detents and pilot adjustable built-in-feel.

Finally it is envisaged that two production units will be manufactured in early 1982 for type approval testing leading to flight cleared units by mid 1982.

ACKNOWLEDGEMENTS

Hightech Components Ltd., Servo House, Mulfords Hill, Tadley, Hants.

"Closed Loop Operation of a Linear Stepper Motor under Microprocessor Control"
Lawrence W. Langley & Howard Keith Kidd
Inland Motor Speciality Products Division, Kollmorgen Corp., Radford V.a., U.S.A.

"Theorey & Application of Step Motors"
Benjamin C. Kuo

"On Self Synchronisation of Stepper Motors"
A. J. C. Bakhuizen
Eindhoven University of Technology

Ferranti Scotland, Thorney Bank, Dalkeith, Midlothian, Scotland.

UTILISATION DE LA COMMANDE VOCALE A BORD DES AERONEFS DE COMBAT

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La Société CROUZET associée à un laboratoire de recherche, le LIMSI (Laboratoire d'Informatique pour la Mécanique et les Sciences de l'Ingénieur) est engagée dans un programme d'étude et d'expérimentation de la commande vocale à bord des aéronefs de combat.

Ce programme dont la partie expérimentale est décrite ci-après, est supporté par les Services Officiels Français, notamment la Direction des Recherches et Etudes Techniques (DRET) et le Service Technique des Télécommunications et des Equipements Aéronautiques (STTE).

1 - OBJECTIF DU PROGRAMME

De nombreux travaux ont montré que l'utilisation de la voix serait un outil très précieux pour résoudre les problèmes de charge de travail des pilotes, de réduction des surfaces de planche de bord et de complexité des interfaces homme/machine dans les aéronefs de combat à haute performance.

L'objectif de notre programme est donc de valider techniquement les méthodes de reconnaissance et de synthèse de parole développées par les laboratoires de recherche dans l'environnement de ces aéronefs.

2 - LES TECHNIQUES

2-1 Reconnaissance

La méthode de reconnaissance développée par le LIMSI a été choisie parce qu'elle nous paraissait la plus performante, qu'elle venait d'atteindre sa maturité, et qu'elle était sortie du domaine de la recherche.

Principales caractéristiques de la méthode utilisée

Il s'agit de reconnaissance globale, au niveau acoustique de mots isolés prononcés par un seul locuteur.

La reconnaissance est :

- Globale : la forme acoustique est reconnue dans son ensemble ; une phase d'apprentissage de la machine est donc nécessaire avant la reconnaissance. Notre méthode peut reconnaître des mots de n'importe quelle langue. Une seule passe d'apprentissage est nécessaire.

- Acoustique : seuls les traits acoustiques entrent dans la reconnaissance, à l'exclusion de niveaux supérieurs, tels le niveau phonétique ; ceci confère une importance particulière aux problèmes de prise de son et d'environnement acoustique.

- Mots isolés : Les mots (ou groupe de mots) doivent être prononcés encadrés de courts silences (200 ms) et doivent être détachés des phrases. Seul ce type de reconnaissance donne actuellement de bonnes performances.

- Monolocuteur : De bonnes performances sont obtenues en laboratoire si c'est le locuteur qui a fait l'apprentissage (une passe suffit) qui effectue la reconnaissance. Ceci implique que les références issues de la phase d'apprentissage devront être propres aux pilotes (cassettes, badges magnétiques ...).

Principe utilisé et résultats actuels

La méthode effectue la reconnaissance sur des sonagrammes compressés.

Les sonagrammes sont la représentation temps - fréquence du signal de parole.

Pour obtenir un sonagramme, les sorties de huit filtres répartis dans la gamme fréquentielle de la parole sont échantillonnées à fréquence fixe.

Avant compression, une seconde de parole représente environ 1 K octets.

Après compression, 1 mot occupe environ 200 octets.

Le programme de reconnaissance, de 4 à 5K, octets effectue la comparaison entre le sonagramme compressé du mot qui vient d'être prononcé et les sonagrammes compressés des mots du vocabulaire de référence qui sont en mémoire.

Il est possible d'ajuster les paramètres internes du programme de reconnaissance pour s'adapter à l'environnement, au type de vocabulaire, et aux performances souhaitées, en particulier sur le taux de rejet (un mot appartenant au vocabulaire de référence n'est pas reconnu lorsqu'il est prononcé) et le taux d'erreur (un mot prononcé est confondu avec un autre mot, différent, appartenant au vocabulaire de référence).

Le délai de reconnaissance est alors fonction :

- des performances souhaitées,
- du nombre de mots du vocabulaire de référence susceptibles d'être reconnus par une syntaxe, qui est l'ensemble des règles logiques (arborescences) qui régissent l'ordre dans lequel les mots du vocabulaire peuvent être prononcés.

lorsque la reconnaissance s'effectue sur environ une quinzaine de mots, le délai moyen est de 200 à 400 ms, si le programme est mis en oeuvre sur un microprocesseur 8 bits de puissance moyenne.

Il faut remarquer que dans l'état actuel de la technique, une machine de reconnaissance de parole n'a pas de performances en propre. Ses performances dépendent bien sûr de la pertinence de ses algorithmes mais aussi et surtout de son contexte et de son utilisation.

Citons en particulier :

- Le bruit.
- La variabilité de la parole sous l'effet de facteurs divers : émotions, accélérations, vibrations, secousses, fatigue.
- Le vocabulaire et ses règles logiques associées (syntaxe).
- Le type même de dialogue (possibilité de confirmer ou de rejeter, qualité du retour visuel, tactile ou auditif, rapidité des échanges).
- La bonne représentativité des références stockées en mémoire.

Actuellement, la méthode est très performante en laboratoire, même sur des vocabulaires très difficiles comportant par exemple une quinzaine de mots dont la prononciation est très similaire.

Sur des vocabulaires ordinaires elle tolère des distorsions de l'accent ou de la durée de prononciation des mots.

Dans les conditions du laboratoire et lorsque la passe d'apprentissage est correctement effectuée, les scores de reconnaissance atteignent régulièrement 100 %.

2-2 - Synthèse de parole

Nous utilisons également une méthode de synthèse de parole développée par le même laboratoire.

Cette technique est issue de machines parlantes appelées ICOPHONES. Ces fonctions sont actuellement remplies par logiciel d'où le nom d'ICOLOG.

Dans un premier temps, nous avons choisi cette technique par opposition aux techniques de compression de parole développées entre autres par les fabricants de composants en raison de la souplesse fournie par la première dans un contexte expérimental.

La voix produite est entièrement artificielle, mais est assez reconnaissable dans le bruit.

L'ICOLOG synthétise le français à partir d'un texte écrit en clair, mais les autres langues peuvent être imitées si on fournit à la machine une écriture en caractères phonétiques.

3 - PROGRAMME EXPERIMENTAL

3-1 - Déroulement

Ce programme expérimental comporte 3 étapes, dont l'enchaînement est présenté sur la première diapositive.

- . Expérimentation en laboratoire d'un dialogue aéronautique avec prise en compte de l'environnement bruité.
- . Expérimentation en simulateur d'un dialogue vocal appliqué à un avion d'armes moderne, et étude des facteurs humains.
- . Expérimentation en vol.

3-2 - Expérimentation en laboratoire

Cette première étape a comporté deux aspects :

- a) Réalisation d'un dialogue interactif mettant en oeuvre des procédures aéronautiques dans un milieu informatique. L'organe principal du dialogue étant une console à tube cathodique et clavier.

Le vocabulaire comportait 119 mots, extraits de procédures tant civiles que militaires, il était doté d'une syntaxe dont le facteur de branchement moyen était de 18 mots.

Les valeurs numériques étaient rentrées en épelant les chiffres.

b) Première prise en compte de l'environnement.

Le milieu ambiant a été abordé de deux façons.

. Des enregistrements de parole, et plus particulièrement du vocabulaire défini, ont été effectués en vol par des pilotes dotés de l'équipement standard (casque + masque à oxygène), et utilisés au sol pour faire de l'apprentissage et de la reconnaissance.

. Des équipements identiques ont été utilisés au sol, en laboratoire, pour dialoguer dans les conditions décrites plus haut.

Les résultats sont présentés sur la diapositive suivante.

Les conclusions de cette première étape ont été les suivantes :

a) Les performances intrinsèques du système apparaissent très bonnes et les performances globales largement suffisantes pour envisager la poursuite du programme expérimental.

b) Diminution des performances due à l'utilisation du masque à oxygène compensée en majeure partie par deux passes d'apprentissage.

c) En vol, pour des accélérations de l'ordre de 2 g, les performances sont voisines de celles obtenues en laboratoire avec masque à oxygène.

d) Les fortes accélérations changent les caractéristiques des mots : reconnaissance difficile au-dessus de 4 g, et les réjections sont systématiques.

e) Il apparaît que la voix est peu gênée par le bruit de l'avion, bruit aérodynamique ou sifflement du moteur ; mais les bruits produits par la respiration dans le masque peuvent par contre être gênants. Les conditions de bruit en vol étaient voisines des conditions obtenues par port de masque en laboratoire.

3-3 - Expérimentation en simulateur

Nous avons réalisé une maquette autonome de dialogue vocal qui sera couplée à l'automne 1981 à un simulateur de vol du Centre d'Essais en Vol d'Istres.

La configuration retenue est décrite dans la diapositive suivante.

La maquette gère l'ensemble des procédures nécessaires à l'apprentissage, à la reconnaissance, à la définition et à la modification des vocabulaires et des syntaxes, ainsi qu'à l'exploitation des essais.

Elle effectue la reconnaissance des ordres, synthétise les messages et est reliée directement au casque du pilote.

Lorsque des actions consécutives à la reconnaissance d'un ordre sont à exécuter dans la cabine, elle transmet les ordres reconnus au calculateur de simulation qui réalise les actions au niveau de la cabine. Ce calculateur pilote la cabine et simule les différentes phases de vol au cours desquelles le dialogue vocal est testé.

En dehors de ses périphériques, la maquette est constituée de trois processeurs :

- un processeur maître qui gère l'ensemble des procédures,
- deux processeurs esclaves, l'un exclusivement affecté à la reconnaissance, l'autre consacré à la synthèse des messages.

Les supports principaux de l'information sont des cassettes magnétiques, qui permettent de charger en mémoire des différents processeurs les vocabulaires et les syntaxes, et qui stockent en cours d'essai les paramètres et les résultats nécessaires à l'exploitation ultérieure.

Un magnétophone enregistre la totalité des essais.

Les fonctions envisagées :

Le thème expérimental choisi est le Mirage 2000.

D'une façon générale, l'utilisation d'un dialogue vocal paraît intéressante dans diverses circonstances :

- Quand la tâche prioritaire est le pilotage et que le pilote ne peut pas lâcher les commandes sans inconvénient.
- Quand le pilote ne peut ou ne désire quitter des yeux un ou plusieurs objets appartenant au monde extérieur.

- Quand les accélérations ou les secousses l'empêchent de manipuler un organe de commande.
- Quand le canal vocal permet une souplesse dans l'exécution d'une fonction ou d'une procédure qui ne serait atteinte par des moyens classiques qu'au détriment d'une surface importante de planche de bord.

Citons quelques cas de vol où ces circonstances se produisent :

- Combat.
- Recherche de contact et d'identification visuelle d'un objectif terrestre ou aérien.
- Percée sur un terrain inconnu dans des conditions de visibilité difficiles avec des aides sol déficientes, ou limitées.
- Suivi de terrain ou vol basse altitude.
- Ravitaillement en vol.
- Patrouille.

Dans le cas précis de l'expérimentation sur simulateur, il a été décidé de reprendre des procédures et des fonctions classiques, déjà assumées par le calculateur de simulation, et d'en réaliser tout ou partie à la voix. Ceci dans le but de permettre une comparaison réaliste entre deux manières d'exécuter la même fonction : la façon traditionnelle, et le dialogue vocal.

Trois types de relations pilote - machine ont été retenus :

- . les interrogations du système.

Le pilote ne veut pas quitter des yeux une cible ou un élément de l'environnement extérieur, mais a besoin de connaître les possibilités qui lui restent pour accomplir telle ou telle manoeuvre.

Exemple : le pilote demande : "ALPHA ?" (pour incidence) ; le système répond par synthèse "18" (18 degrés) ou encore : "HAUTEUR ?" (garde par rapport au sol), réponse : "1200 PIEDS".

Nous pensons que ce type de dialogue peut être amené à prendre de l'importance dans le futur, même pour de simples problèmes de gestion de vol (possibilité de déroutement par rapport à la route prévue, réserve de pétrole, etc...).

- . les commandes, configuration systèmes et introduction de données :

Les commandes dites "temps réel" demandant une exécution immédiate ne seront pas traitées à cause de la double exigence d'un délai de réaction extrêmement court et d'une très haute sécurité de fonctionnement.

Les fonctions recensées concernent :

- La présélection et la gestion des armements.
- La navigation finale sur les objectifs.
- La gestion des modes sur divers écrans de visualisation.
- Certaines commandes de pilotage automatique.

Citons quelques exemples extraits de ce dernier cas :

Capture d'une pente de montée de 35 degrés :

"PENTE [] PLUS [] TROIS [] CINQ"

[] signifie un silence de 200 ms minimum.

Maintien de l'altitude actuelle :

"ALTITUDE ACTUELLE"

- . les pannes :

Elles donnent lieu à la synthèse d'un message dans le casque pilote. On s'est efforcé de lui donner un haut degré de signification :

Exemple : "UTILISE L'HORIZON SECOURS" en cas de panne de centrale de navigation en mode NAV/APPROCHE ou : "MISSION 530 IMPOSSIBLE" dans le cas de l'indisponibilité du missile au moment d'une présélection, ou après celle-ci.

Etude de l'influence de l'environnement et des facteurs humains

Parallèlement aux essais sur simulateur seront poursuivis :

- L'étude de l'influence des accélérations (en centrifugeuse) et des secousses et vibrations.
- L'étude des environnements sonores plus difficiles (hélicoptères).

3-4 - Expérimentation en vol

La réalisation d'une maquette embarquable a été entamée et des essais en vol pourraient avoir lieu dès le début de l'année 1982.

Cette maquette permettra de tester le dialogue vocal dans les conditions réelles d'emploi.

La diapositive suivante montre l'organisation choisie. Le support des informations variables (vocabulaire du pilote, résultats d'essais ...) est constitué par des cassettes. Un enregistreur/lecteur est embarqué à cette fin sur l'avion.

Un banc sol a pour mission de préparer et d'exploiter les vols.

Le programme est actuellement en cours de définition.

Les expérimentations en vol se dérouleront en deux étapes :

- une étape dite ergonomique destinée à valider la technique avec toutes les contraintes de l'environnement réel,
- une étape fonctionnelle, où l'équipement sera effectivement couplé à des systèmes de bord ; elle doit amener les éléments de réflexion nécessaires à l'utilisation future de la parole dans les avions d'armes.

Cette étape sera réalisée en collaboration étroite avec la SFENA et le CENTRE D'ESSAIS EN VOL.

COMMAND-RESPONSE DATA TRANSMISSION APPLIED TO MECHANICAL SYSTEMS MANAGEMENT EFFECT ON THE CREW/SYSTEM INTERFACE

by

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SUMMARY

The use of digital data transmission techniques for aircraft systems is becoming more widespread as the full effect of the micro-electronics revolution is felt. The availability of low cost, high reliability micro-electronic digital devices has made digital data transmission systems an attractive proposition for aircraft data handling systems. Apart from the advantages of accuracy and high data rates which digital devices offer, significant improvements in system performance, weight and reliability are possible. Initially the use of digital data systems was confined to aircraft avionics systems embracing navigation, weapon aiming and flight control functions. More recently the application of these techniques has been extended to the centralized control of mechanical system management. This joint BAe Warton/Smiths Industries Cheltenham paper will deal with the example of an engine failure and shut-down in flight which will demonstrate the interactive nature of data handling between two data buses and the effects upon advanced cockpit displays.

1. INTRODUCTION

In today's generation of combat aircraft, mechanical systems or 'Utility Systems' - such as those associated with Powerplant management, Secondary power, Environmental control, Hydraulic and Fuel gauging/Management - have been designed as individual systems and consequently have their own dedicated control units. The result is a large number of dedicated single function Line Replaceable Units (LRUs) and a large number of dedicated cockpit instruments which tend to be interconnected by large cable looms. In addition, there are discrete switches and warning lamps which tend to proliferate throughout flight development. In recent aircraft (Jaguar, Tornado) the situation has been redressed but could still be improved. Future high performance combat aircraft will require increased automation from these utility systems in order to significantly reduce pilot workload (especially in a single cockpit configuration). As less space is available for equipment in the fuselage equipment bays, and because of reduced cockpit panel area, multifunction displays and controls will be required.

The above demands together with the increasing use of serial digital data transmission systems means that alternative design methods must be applied to utility systems.

A considerable amount of research work has been progressing at British Aerospace, Aircraft Group, Warton Division for the past two years, under both UK Ministry of Defence (MOD) and Private Venture funding into alternative methods of controlling the utility systems. The most favoured approach for realising this control is to consider a Central Management System which controls all of the utility systems.

The result of this approach is the Integrated Control of Mechanical Systems (INCOMS) which is based on a number of microprocessor-based computer systems that are geographically dispersed through the airframe. These INCOMS Processors will operate independently as individual computing centres and will be interconnected via a MIL-STD-1553B data bus (or its derivative). Some of these processors will act as remote terminals, collecting raw data for onward transmission (via the data bus) to their designated processing centre(s).

The main objectives of adopting INCOMS are:-

- (a) To improve system reliability,
- (b) To reduce pilot workload by introducing a higher degree of automation,
- (c) To reduce wiring and weight,
- (d) To ease the maintenance task by providing a self-test and fault diagnosis capability. This would provide status indications to flight and ground crews to establish pilot confidence in correct system operation (even under fault conditions); and it would also reduce the maintenance time,
- (e) To improve system performance,
- (f) To increase flexibility,
- (g) To reduce the overall cost.

INCOMS will have a significant impact on the crew-system interface and thus upon the requirements for cockpit displays and controls. A fully automatic management system with the ability to operate without significant degradation under fault conditions will reduce the necessity for the continuous display of status information. A digital computing system with access to the cockpit via MIL-STD-1553B will enable the pilot to communicate with systems via non-dedicated or multifunction switches.

A need will exist for surfaces that allow system information to be displayed as and when required, in a format that will allow rapid assimilation of data by the pilot. Colour could be used for emphasis, especially for changes in status, if it were considered beneficial and cost-effective. Dedicated controls can be limited to those requiring instinctive action; whilst access to the system (in response to prompts, to modify systems' actions or to request further information) can be achieved by using multifunction keyboards or active displays.

The systems that are being considered in the global term 'Utility Systems' are shown in Figure 1. The systems range from the very complex, e.g. Fuel Management, to the very simple, e.g. Arrestor Hook. The one thing that all of these systems have in common is that they must conform to the requirements mentioned above.

2. INTEGRATED CONTROL OF MECHANICAL SYSTEMS (INCOMS)

A brief description of the 'total systems' approach that has been adopted at BAe, Warton and a description of an ideal system follows, to give some background to the technical aspects of the work carried out to date.

Figure 2 shows a block diagram of a typical integrated avionics system envisaged for future aircraft, but with the utility systems shown as they exist on contemporary aircraft - i.e. JAGUAR/TORNADO. These utility systems have individual sets of components and control elements. Only five control elements for the utility systems are shown, whereas on existing aircraft one set of control hardware would be expected for each of the systems. To connect the individual systems to the cockpit requires a considerable amount of discrete wiring.

To avoid this situation, all the control elements could be combined into a single block called Utility Systems Management (see Figure 3), and that block connected as a terminal onto the main Avionic Bus. If recognition is taken of the distribution of components throughout the airframe, it will be seen that this method is unacceptable for at least three reasons:-

- (a) The large amount of discrete wiring involved,
- (b) The concentration of wiring at the central block,
- (c) The susceptibility of the central block to damage or failure.

These problems can be overcome by the Integrated Control of Mechanical Systems (INCOMS) whose system consists of a number of data acquisition and computing devices at strategic locations throughout the airframe (see Figure 4).

This will enable components local to the devices to be connected to the most suitable (i.e. nearest) device, thereby restricting discrete wiring to local areas. A data acquisition and computing sub-system can now be considered which consists of a number of INCOMS processors (the current work at BAe, Warton indicates that 6 may be an optimum number) which are interconnected via a MIL-STD-1553B data bus. This bus is in turn connected to the main Avionics Bus via a Bus Interface Unit (BIFU) which can also act as a Bus Controller.

An example of the type of device that could be envisaged as being an INCOMS processor is shown in Figure 5. The interface with the data bus, CPU and memory, and the interfaces with the mechanical systems' components are shown. These interfaces will allow receipt of information from discrete, analogue, digital and optical devices/sensors, and the Power Control interface will allow power to be switched to devices such as valves, pumps, etc. In an ideal system each INCOMS processor would be hardware identical with its individual program store taking account of the various peripheral components in that processor's aircraft location.

This system offers a minimum hardware, minimum wiring solution that can be envisaged for a future combat aircraft.

3. EXAMPLE TO SHOW HOW INCOMS WOULD INTERFACE WITH THE COCKPIT

The interconnection of the INCOMS bus to the main avionics bus, as shown in Figure 4 requires a detailed study of the relative data handling priorities between the buses at a particular stage of a flight, together with a complete, detailed, understanding of the design and implementation of the overall system.

Such detail would clearly not be suitable for presentation at an AGARD symposium, however the factors involved are nevertheless of importance to both systems engineers and operators. To present simply the factors involved, a worst-case example has been chosen which will highlight a marked change in pilot priorities due to changing flight conditions.

The artificial example chosen to illustrate how INCOMS may interface with the cockpit is that of a spin, followed in this case by double engine flame-out. It is assumed that this has occurred at low speed and high altitude.

NOTE: The probability of this occurring is remote, but it is an example that can ideally illustrate the interface between INCOMS and pilot.

The pilot is, therefore, plunged into a situation where his priorities shift from relatively low workload to very high workload applied to re-establishing vital aircraft systems necessary for flight. This shift in priorities alters the data flow requirements between the main avionics bus and associated Multi-Function Displays (MFD), to that between INCOMS bus, avionics bus and MFDs.

For the purpose of this example certain assumptions have been made, namely:-

- (a) The aircraft is twin engined.
- (b) The display layout for the cockpit is as shown in Figure 6.
- (c) The information associated with the incident is displayed using two multicolour MFDs, though a detailed ergonomic study could possibly reduce this to one.
- (d) No particular method has been defined for the use of colour; however, for the purposes of this exercise:-
 - red is used for warnings,
 - green is used for 'GO' status,
 - pointer and dial displays have been preferred to strip-type displays.
- (e) Commands are displayed on the left-hand MFD and are surrounded by an occulting box. Indications are normally displayed on the right-hand MFD and are in normal print.
- (f) A large degree of automation has been assumed to prevent excessive pilot workload.

It must be stressed that this is an illustrative example and does not necessarily reflect the overall display philosophies being adopted by BAe Warton and Smiths Industries in their future aircraft studies.

The sequence of events following a double engine flame-out is shown in Figure 7. As far as possible INCOMS controls the initiation of recovery action, including the automatic selection of the Auxiliary/Emergency Power Unit (AEPU). At vital junctures the system displays the relevant recovery information to the Pilot; the method of presentation being dictated by whether:-

- (a) Executive action is required,
- (b) Warnings are required,
- (c) Information is to be displayed.

In this sense, the display philosophy could be considered as a semi-automated process applied to existing flight crew 'flip-cards'.

The sequence of events that occur following a double engine flame-out is shown in Figures 8, 9, 10, 11, 12 and 13. These figures show one way in which the relevant information could be displayed to the pilot.

An explanation of Figures 8 to 13 inclusive is given below:-

When INCOMS detects that engine RPM has dropped to a level such as flight idle, and that a high rate of deceleration exists in both engines, it automatically starts the AEPU to provide electrical and hydraulic power whilst recovery action is initiated. Meanwhile, the igniters automatically fire in an attempt to relight the engines. It is assumed for this example, that a relight is not achieved but that the pilot recovers from the spin. Whilst recovering from the spin INCOMS displays the fact that both engines have failed to relight and that the pilot must effect a relight. The executive action to the pilot is 'SHUT HP COCKS'. He is also informed that the AEPU is running and that the electrics and hydraulics are on line. Engine instrumentation is also available (see Figure 8).

NOTE: HP Cocks are shut down to prevent fuel leakage whilst the engines are not running.

When INCOMS receives the input from the throttles that HP Cocks are shut, it changes the display to inform the pilot that he must select 'IDLE' on both engines, in readiness for an attempted engine restart (see Figure 9).

NOTE: The system does not allow fuel to be supplied to the engines until a predetermined RPM is attained and TBT does not exceed a certain level.

When INCOMS receives the input from the throttles that 'IDLE' has been selected, it changes the display to inform the pilot that an engine start can now be attempted. The pilot selects engine start by depressing the identified 'soft' Multi-function key.

By the selection of engine start, the AEPU starts to drive the gearbox on No.1 engine, say. When INCOMS senses that engine RPM is above a certain level (i.e. 25%), it supplies fuel to the engines automatically (see Figure 10).

NOTE: TBT should not exceed a certain level during the start. If it does, the system automatically shuts the engine down.

When 'START' has been selected, INCOMS senses this and informs the pilot that START is in progress. Of course, he can confirm this himself by monitoring the engine instrumentation (see Figure 11).

INCOMS detects that No.1 engine is up to speed and automatically engages cross-drive between the two engine gearboxes. The pilot is then informed that cross-drive has been engaged. An indication is still visible informing him that START is in progress (see Figure 12).

INCOMS automatically initiates a start routine on the second engine, No.1 engine now drives No.2, and when engine No.2 has attained a certain RPM (i.e. 15%) and is below a certain TBT, the system supplies fuel to No.2 engine and it is started.

When No.2 engine is up to operating speed, the AEPU and cross-drive are disengaged automatically by INCOMS and the pilot is instructed to return to his original flight mode. Upon selection of a flight mode, the displays will revert to their normal format.

4. SYSTEM DATA FLOW

Figure 14 shows a possible system architecture and the data parameters associated with the events already described. Two Multi-Function Displays/Waveform Generators (MFD/WFGs) are shown on the avionic bus though bus loading calculations assume that three MFD/WFGs are fed display information. There would also be more than one Bus Interface Unit (BIFU) for integrity reasons. Six Processors are shown as described earlier. For this example Processors 1, 2, 5 and 6 also gather information and enable the necessary data to be transmitted on the bus. Data would also be transferred between Processors which duplicate a particular management function. It has also been assumed that all the management information received by one Processor is also supplied to another which is also capable of undertaking that management function. In this manner the system effectively has a dual redundant management capability for all general aircraft functions so that the systems may still be controlled should one Processor fail.

Figure 15 shows the bus loading associated with the avionics bus for a typical flight situation and are based upon work carried out jointly by British Aerospace and Smiths Industries. The contribution of each major system to bus traffic is also shown. These calculations assume a data iteration rate of 32 Hz for most transactions: some weapon aiming functions have been calculated at a 64 Hz iteration rate, though in this case the bus loading of 45.9% is much higher than would be allowed in a practical system. The contribution of the utilities system is 117.8 msec/sec comprising a load of 33.3 msec/sec from the avionics bus to the BIFU and 84.4 msec/sec load from the BIFU to the three WFGs.

The bus loading shown in Figure 15 and the timing diagram of Figure 16 (not to scale) shows that there are a large number of useable gaps of 500 μ sec or more which could be used for interrupt purposes, should this be considered necessary. The longest time between these gaps is approximately 4 msec.

The bus loading of the INCOMS data bus is shown in Figure 17. This bus loading is typical of a system managing around 650-700 variables in the utility systems. The contribution of each of the major systems is shown and a data iteration rate of 32 Hz has been assumed as for the avionics data bus. The total loading for the utilities data bus is 381 msec/sec or 38.1%. However, the BIFU has to handle data transfers to and from the avionics bus as well as control transactions on the INCOMS bus. The total loading on the BIFU is therefore 49.9% if the data iteration rate of 32 Hz is used on both data buses. The question of BIFU loading for dual redundant architectures is under further study.

Discounting the use of priority interrupts and assuming fixed data transfer schedules; the worst case for an item of information to be transferred from a utilities transducer to the cockpit displays will be twice the time elapsed for one iteration, i.e. not greater than $2 \times \frac{1000}{32}$ or 62.5 msec (1/16 sec) (see Figure 18). In most cases the elapsed time will be much shorter than this. For data transfers from the displays to a switch or actuator the worst case is the iteration rate of the avionics bus plus the delays in transmitting the data from the BIFU to the processor. This delay will be only slightly greater than 31.25 msec/sec (1/32 sec). The automatic selection of emergency systems initiated by the BIFU will be marginally greater than 31.25 msec.

These delays are minimal compared to pilot assimilation and reaction times, and are thought to be acceptable for implementation in a realistic design. No penalties are therefore envisaged in adopting this type of design.

5. CONCLUSION

- * In the example chosen, a simplex Bus Interface Unit (BIFU) has been assumed whereas in practice dual redundant BIFUs would be utilised for integrity purposes. These could result in a slightly higher bus loading dependent on the redundancy scheme selected. Redundancy of displays has been considered; three Waveform Generators (WFGs) have been assumed to be given all the available utilities information available.
- * Realistic assumptions have been made regarding the types of display available and the use of multi-function 'soft' keys.
- * In the example, system reconfiguration has not been considered. Realistic system design architecture would allow for a sufficient degree of redundancy and fault tolerance.
- * A large degree of system autonomy has been assumed and a philosophy adopted which results in an automatic paging system portraying information akin to existing hand-held emergency flip cards.
- * The relative loading of the avionics and utilities data buses is acceptable. The loading of the BIFU has also been calculated and the delays of information transfer to and from the displays found to be acceptable.
- * The question of dedicated links to the displays has not been considered. Though there may be a requirement for dedicated links in some cases, it is believed that suitable system designs may be derived which raise integrity levels such that dedicated links may not be required.

Certain assumptions have been made during the course of this presentation which will require validation before being applied to a particular aircraft project. Work is being undertaken at Smiths Industries and British Aerospace to this end.

SLIDES/FIGURES

- 1 LIST OF UTILITY SYSTEMS
- 2 CONVENTIONAL CONTROL OF UTILITY SYSTEMS
- 3 CENTRALISED UTILITY SYSTEMS MANAGEMENT
- 4 GEOGRAPHICAL LOCATION OF INCOMS PROCESSORS
- 5 POSSIBLE INCOMS PROCESSOR ARCHITECTURE
- 6 SIMPLIFIED COCKPIT LAYOUT
- 7 SEQUENCE OF EVENTS FOLLOWING DOUBLE ENGINE FLAMEOUT AND SPIN
- 8 DISPLAY FOLLOWING DOUBLE ENGINE FLAMEOUT
- 9 DISPLAY COMMANDING THROTTLE SELECTION
- 10 DISPLAY COMMANDING ENGINE START
- 11 DISPLAY FOLLOWING ENGINE START INITIATION
- 12 DISPLAY SHOWING NO.2 ENGINE START
- 13 DISPLAY SIGNIFYING RESELECTION OF FLIGHT MODE
- 14 SYSTEMS ARCHITECTURE AND DATA PARAMETERS
- 15 TYPICAL BUS LOADING (AVIONICS BUS)
- 16 AVIONIC BUS TIMING
- 17 UTILITIES SYSTEMS BUS LOADING
- 18 TYPICAL INFORMATION TRANSFER TIMING

ENGINE AND ASSOCIATED SYSTEMS

Engine Intake De-Icing
 Engine Starting and Ignition
 Engine Controlled Services
 Thrust Reverse Control
 Fire Detection and Suppression System
 System Warning and Health Monitoring

HYDRAULIC AND ASSOCIATED SYSTEMS

Hydraulic Utilities
 Hydraulic Control
 Depressurisation
 Brakes and Anti-Skid Control
 Undercarriage Control and Indication
 Nonwheel Steering
 Flight Refuelling Probe
 Systems Warning and Health Monitoring
 Canopy Control

FUEL SYSTEM

Fuel Booster Pumps
 L.P. Cocks - Shut Off Valves
 Re/Defuel Transfer
 Fuel Dump
 Fuel Gauging
 Fuel Flowmetering
 Hit Detection and Suppression
 System Warnings and Health Monitoring

OXYGEN SUPPLY SYSTEM

Nuclear/Chemical/Biological Protection

AIR AND ENVIRONMENTAL CONTROL

Cabin Temperature Control
 Temperature and Pressure Safety Control System
 Rain Dispersal
 Canopy Standby Demist
 Equipment Bay Cooling
 System Warnings and Health Monitoring

MISCELLANEOUS

Cockpit Lighting
 E/L Panel Lighting (Instruments)
 Landing and Taxi Lights
 Anti-Collision Lights
 Navigation Obstruction Lights
 Windscreen Heating
 Probe Heating
 Seat Adjustment
 Arrestor Mask
 Canopy Seal
 Windscreen Wash

SECONDARY POWER SYSTEM

Engine Gearbox and Crossdrive
 Auxiliary Power Unit/Emergency Power Unit

FIGURE 1 LIST OF UTILITIES SYSTEMS

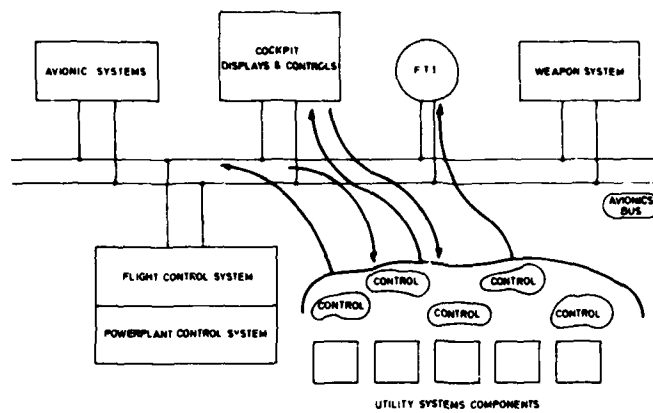


FIG. 2 CONVENTIONAL CONTROL OF UTILITIES SYSTEMS

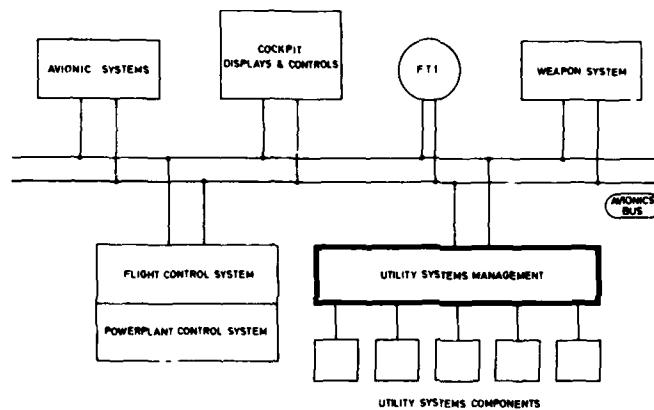


FIG. 3 CENTRALIZED UTILITIES SYSTEMS MANAGEMENT

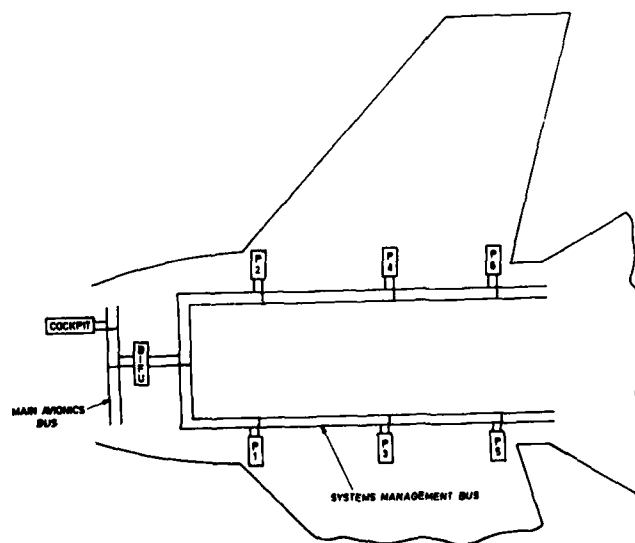


FIG. 4 GEOGRAPHICAL LOCATION OF INCOMS PROCESSORS

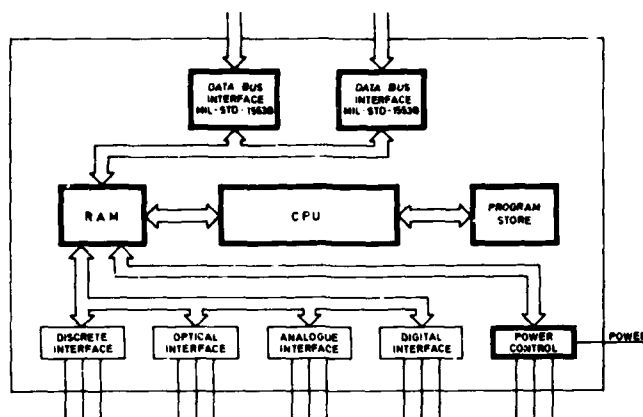


FIG. 5 POSSIBLE INCOMS PROCESSOR ARCHITECTURE

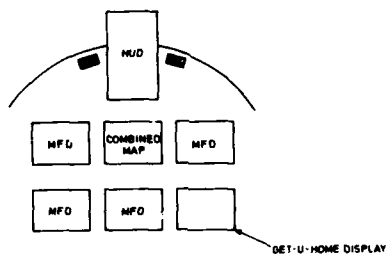


FIG. 6 SIMPLIFIED COCKPIT LAYOUT

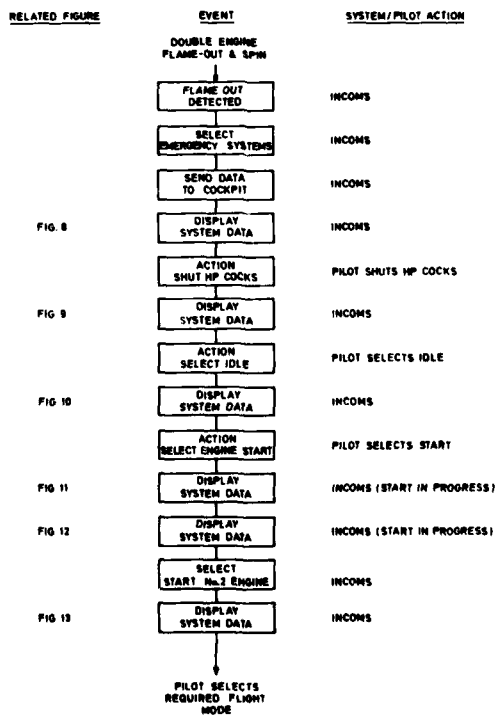


FIG. 7 SEQUENCE OF EVENT FOLLOWING DOUBLE ENGINE FLAMEOUT AND SPIN

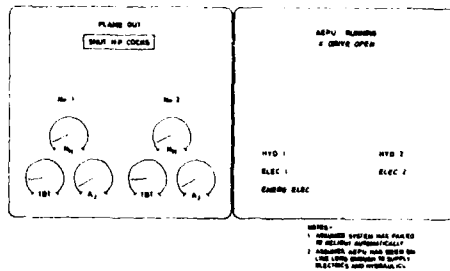


FIG. 8 DISPLAY FOLLOWING DOUBLE ENGINE FLAMEOUT

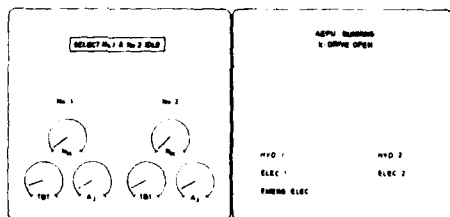


FIG. 9 DISPLAY COMMANDING THROTTLE SELECTION

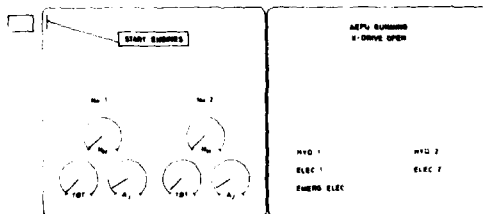


FIG. 10 DISPLAY COMMANDING ENGINE START

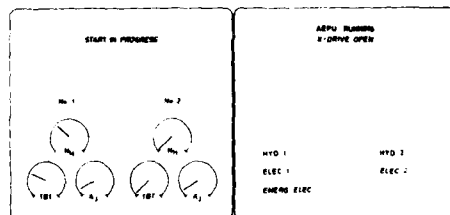


FIG. 11 DISPLAY FOLLOWING ENGINE START INITIATION

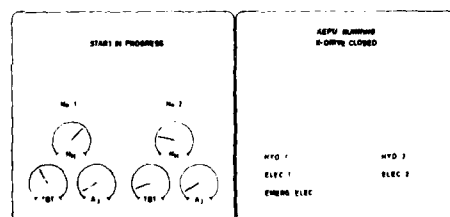


FIG. 12 DISPLAY SHOWING NO. 2 ENGINE START

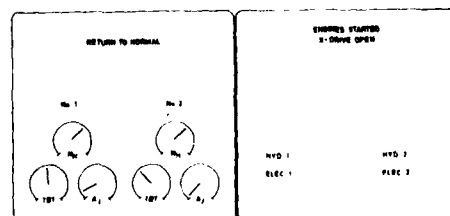


FIG. 13 DISPLAY SIGNIFYING RESELECTION OF FLIGHT MODE

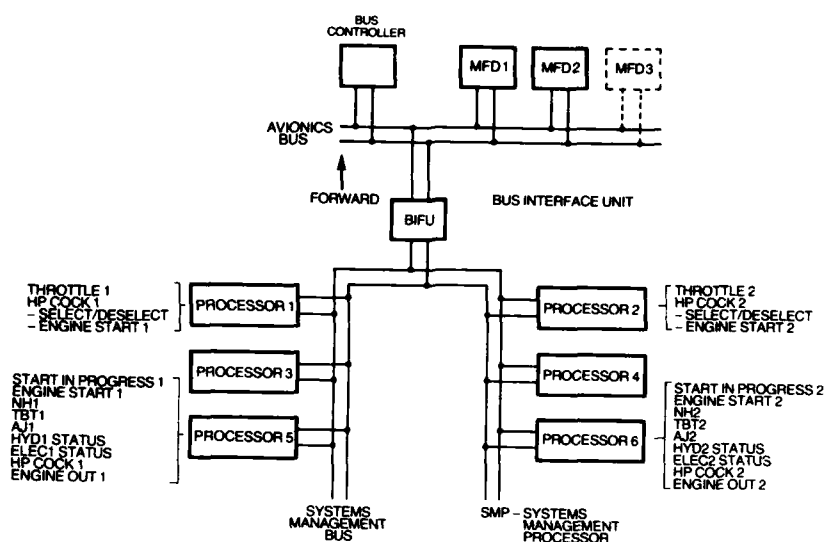


FIG.14 SYSTEMS ARCHITECTURE AND DATA PARAMETERS

Sub-system	Bus loading (1)
NAV MAN/INS 1	102.9
NAV MAN/INS 2	
Radar	16.2
Stores management	68.7
Utilities	117.7
Misc.	150.8
Total	459.3
Equivalent Bus loading	45.93%

Notes (1) Timing in m.sec./sec. of Bus operation

General aircraft systems contribution to Bus loading:

From Avionics Bus : 52 words at 32 Hz
 $= 52 \times 20 \times \frac{32}{1000} \text{ m.sec./sec.}$
 $= 33.3 \text{ m.sec./sec.}$

From Utilities Bus = 44 words at 32 Hz to 3 WFGs
 $= 44 \times 3 \times 20 \times \frac{32}{1000} \text{ m.sec./sec.}$
 $= 84.4 \text{ m.sec./sec.}$

Total Contribution = 117.7 m.sec./sec. or 11.8%

FIG.15 TYPICAL BUS LOADING (AVIONICS BUS)

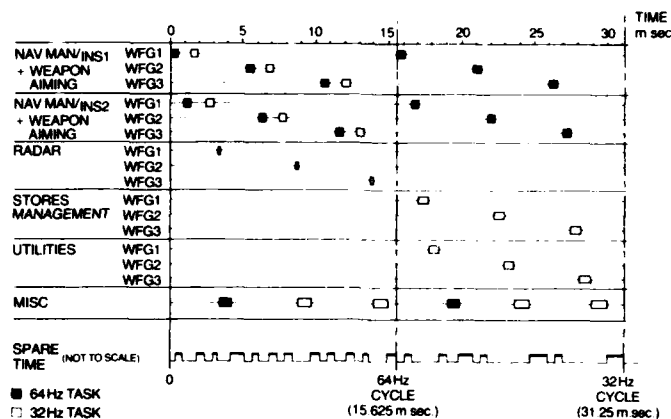


FIG. 16 AVIONIC BUS TIMING

	Loading	BIFU Loading =
Hydraulics	31.0	381.0 m.sec./sec.
Brakes	37.0	UTILITIES BUS
NWS	23.0	+ 117.7 m.sec./sec.
Fuel	136.0	AVIONICS BUS
Engine Associated	42.0	= 498.7 m.sec./sec.
Environmental	13.0	or 49.87% loading
Undercarriage	29.0	(approx. 49.9%)
Cockpit	23.0	
Miscellaneous	47.0	
Total	381.0 m.sec./sec.	
	38.1% Bus loading	

FIG. 17 UTILITIES SYSTEMS BUS LOADING

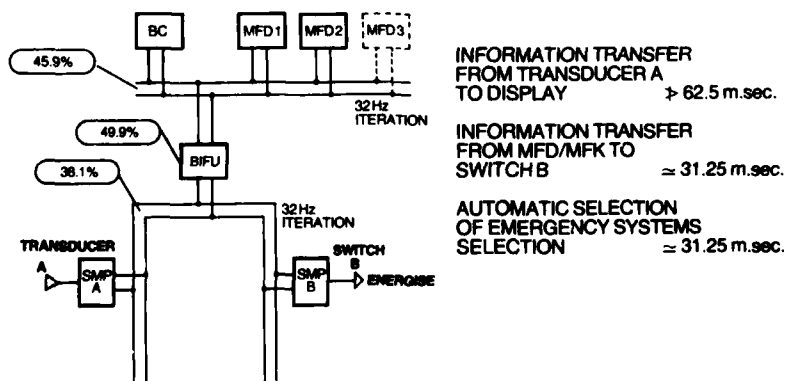


FIG. 18 TYPICAL INFORMATION TRANSFER TIMING

THE INTELLIGENT USE OF INTELLIGENT SYSTEMS: PROBLEMS IN ENGINEERING MAN/MACHINE SYMBIOSIS

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SUMMARY

The objective of this paper is to describe a methodology to structure the process of designing "intelligent systems". This methodology was generated in the course of several specific projects undertaken to develop such systems for a variety of airborne platforms. The general goals of these projects are to improve system performance by enhancing the effectiveness of information management within the total avionics systems. In this paper we summarize results from these studies and relate the knowledge gained to a systematic design/evaluation approach.

INTRODUCTION: WHY INTELLIGENT SYSTEMS?

Technological advances in the past several decades have resulted in the development of many systems which far exceed the capabilities of man to use them. This is most evident in military systems, particularly in airborne systems where tactical crewmembers have a severely restricted time frame in which to perform their required functions. In addition to this compressed time-horizon, processor and control/display advances have created an information overload of such magnitude that operators have become unable to cope with the high information rate and volume produced by their avionics systems. As a result, they find themselves unable to make the necessary high quality decisions in the time available. Personnel most affected are those such as tactical officers, who have the task of analyzing incoming sensor information, assessing the current situation and determining the most effective tactical maneuvers.

As an example, consider just one task which an F-14 tactical flight officer handles during a mission. During assessment of threats posed by approaching targets, an attack planning function must be performed, in which an optimal course of action is determined. A series of individual judgments must be made during this function, most requiring evaluation and resolution in a matter of seconds. These decisions include:

- What are the target threat values?
- How should targets be prioritized?
- Should aspect maneuvers be initiated to acquire more targets for assessment?
- What strategies could the enemy be using to hide high value targets?
- Can launch acceptability regions be acquired?
- What subset of targets should be attacked?
- What is the best position for missile launch? and
- What vectors maximize tactical gain?

For each of these individual decisions, a multitude of variables (e.g., time, fuel requirements, mission objectives, enemy objectives, missile utilization, defense strategies after missile launch) must be weighted with the consequence of possible outcomes evaluated. Although an overwhelming amount of data concerning track files, aircraft status, target classification and environmental parameters are available for the operator to use in the decision process, solutions must be derived, critical variables must be combined and possible actions generated and evaluated within extremely brief time windows.

The extensive information processing load involved in screening and displaying data, integrating threat assessments and evaluating alternative actions will, in a complex situation, far exceed capabilities, of even a trained and experienced operator. It has become necessary to design systems in a way which compensates for man's inherent disadvantages in maintaining pace with technological progress. Present attempts at automation have provided only a partial solution to the problem. Automation of specific tasks (e.g., processing and screening raw sensor data, routine record keeping, and recall of technical and tactical information) has proven to be effective, and has often provided more reliable performance than did the human operator. But these are only minor data processing functions, and their automation does not lighten the decision demands and cognitive processing requirements placed upon the operator. To do this, it is necessary to develop automated systems or subsystems that do independent "thinking" and problem solving at an equivalent (or greater) level of performance as man.

In 1960, Licklider [1] defined a provocative concept of future human and computer interactions which he called "man-computer symbiosis". Instead of man-machine systems merely providing a mechanical extension of the human, he posed that the two

dissimilar "organisms", human brains and computing machines, could be coupled in a close cooperative partnership to perform intellectual operations. The aims of this symbiosis were to let the computation capability of computers facilitate formulative thinking (as they facilitate analysis of formulated problems) and allow both the human and computer to cooperate in making decisions and controlling complex situations in a more effective manner than man alone could perform. In his picture of the man-computer partnership, the computer's role was to perform tests of models, transform data, and make statistical inferences while the man's role was to generate hypotheses or models, provide necessary data, and set goals and criteria for analysis. In other words, man asked the questions and computers provided the answers.

When the concept was first proposed, the practicality of symbiosis was limited by the restricted software and hardware capabilities of the day (e.g., the impossibility of real-time computational analysis of problems as they arose). The ability of computers to perform the intellectual tasks required for decision-making or problem solving was another limiting factor. During the last twenty years, tremendous technological strides have been made in the development of interactive time-sharing, microprocessors, VLSI (very large scale integrated circuits), data management, programming languages, artificial intelligence, speech recognition, decision aids, and display equipment. These evolutionary leaps virtually eradicated previous restrictions for developing symbiotic systems and expanded the scope of the type of cooperative interaction which could be achieved between man and computer. Instead of just performing elementary evaluations of courses of actions, computers can now be utilized to perform functions which allow them an intelligent, active role in solving complex problems. Techniques are available which permit computers to generate their own models, ascertain how to best test those models, and determine the implications of the models' output. While such functions appear to make a system intelligent, they do not replace the need for an operator. Man is still required to assess the validity of automated processing results, to incorporate heuristics into the system, and to incorporate novel information. Most importantly, man is needed to perform abstract problem solving tasks which computers, as yet, can not perform due to their limited flexibility. With these intelligent systems, man asks and answers questions, and computers ask and answer questions. The only difference between them lies in the capability and limitation of each to perform specific functions. For example, computers can correlate multiple sets of data to find specific trends (as required in target classification tasks) better than man. But in some (unanticipated) conditions the computer algorithm may perform poorly. When this occurs, it would be the operator's responsibility to utilize his judgment or obtain other verification before tactical actions can be taken on the basis of the computer's assessment. Although the algorithm may be intelligent enough to alert the operator when a poor result has been obtained, and may even recommend a remedial course of action, a human operator is still required to make the final evaluation, especially when risks of errors have high stakes as in military situations.

The current state-of-the-art allows designers to develop primitive versions of the "intelligent" symbiotic systems as suggested above, thus making Licklider's vision a reality. But for them to become viable, system designers must determine how to design these systems and how to allocate decision functions (properly) in order to achieve the necessary effective, cooperative association.

DESIGNING INTELLIGENT SYSTEMS

The "Decision Augmentation Systems" (DAS) program at the Naval Air Development Center, was established to address the issues of developing and designing intelligent systems to augment airborne decision-making performance via man-computer symbiosis. The program is based upon the premise that symbiosis requires especially rational design engineering to avoid the trap of inappropriate automation, i.e., automation which contributes to rather than solves problems to which it is directed. While it is now widely accepted that intelligent systems can augment human functions and potentially relieve current operator workload problems, it is not widely understood that inappropriate engineering of such systems can materially worsen the already severe operator workload situation. Previous efforts toward cockpit automation have exhibited a distinctly piecemeal approach. Typically, functions associated with only a single subsystem or a single sensor were addressed in isolation, without consideration of the associated operator functions or of the implications of other automation developments. Ironically, this approach often left operators with only those tasks not understood well enough to automate -- often precisely those most in need of computer support.

Determining where and how decision augmentation should be used requires a systematic, multi-step approach. The approach must consider the operator's specific needs for assistance in a broad range of mission contexts; it must generate candidate ways of addressing these needs; and it must provide ways of rationally selecting from among the candidate designs according to the specific constraints of the environment of ultimate implementation. A general sequence of steps to follow is to:

- Identify the Characteristics of the Required Solution,
- Select Algorithmic Approaches to Generate the Solution, and
- Evaluate each Design Alternative for Effectiveness, Feasibility of Implementation, and Impact on the Operator.

There are many alternative forms of a given symbiotic system which can be defined both with regard to the underlying algorithmic techniques and to allocation of specific functions to operator and computer. To insure that the desired results are ultimately obtained, it is necessary to select from among promising automation and augmentation system configurations by developing and applying objective criteria and methods. The systematic evaluation of each proposed intelligent system throughout its development cycle will insure that the desired effects on operator/system performance are being achieved.

Each of the steps listed above requires analysis and evaluation techniques specifically tailored to the design of intelligent decision augmentation systems. Relevant analysis mechanisms range from formal methods for front-end analysis and problem definition, through part-task simulation and application of computer models, to use of evaluation methods employing high-fidelity hardware simulators and operational software. In addition to these performance-oriented methods, there are critical considerations in gaining user-acceptance of intelligent systems, and in planning for degraded mode operations. The specific problems in the design process on which the remainder of this paper focuses are the initial generation of system design alternatives, the identification of the characteristics of required solutions, the selection of algorithmic approaches which might be applicable, and the preliminary evaluation to determine the effectiveness and feasibility of candidate designs. These aspects are discussed at a general level in the following section. In the subsequent section, specific studies which demonstrate these design phases will be presented in more detail.

Identifying Characteristics of Required Solutions

The development of designs for intelligent decision augmentation systems should be guided by a design philosophy which is consistent and appropriate to the task. To date, the development of such systems has been guided primarily by the philosophy of "top-down" design. This philosophy advocates that systems first be designed in abstract and logical terms, completely independent from the physical considerations of their implementation. Technical and implementation details are then carefully added one level at a time so as to insure their complete consistency with the desired logical properties of the system. The popularity of this approach stems from its usefulness in generating system designs with high integrity and clear logical organization, and its ability to provide a much-needed structure to the design and development processes.

There are, however, key shortcomings to the top-down approach when applied to the development of intelligent decision augmentation systems, particularly in military contexts. These shortcomings stem from the fact that the decision augmentation system must "fit" into some already-existing larger tactical, command and control, or avionics system. In such cases, the DAS should not be designed "in a vacuum" (as top-down design implies), but rather in full cognizance of the operational constraints imposed on it by the system with which it must ultimately integrate. Such a process of designing to physical implementation constraints can be termed a "bottom-up" design approach.

In designing and developing an intelligent system the viewpoints of both the top-down and the bottom-up approaches must be combined into a single design methodology. Top-down principles should be followed in order to structure the design/development process and ensure a clear organization of the system. Bottom-up principles should be followed to ensure that the resulting system will be consistent with the environment(s) in which it would ultimately be used. A design approach which combines these top-down/bottom-up principles is pictured in Figure 1. The goal of this approach is to allow the design process to move smoothly and systematically from the identification of an operational problem (i.e., notion of what needs to be accomplished by use of an intelligent system) to a set of clear specifications of the characteristics of an actual system to solve the problem.

Three primary top-down factors or considerations are indicated in Figure 1. The first consideration is the detailed structure of the problem with which the system will deal. Of particular concern are the informational requirements and characteristics of the problem -- its specific inputs, outputs, parameters, and decision variables (those whose value must be specified). These data define the information which is relevant to the solution of this problem and which therefore must be somehow treated in the system design. The second top-down factor is the logical input/output requirements of the specific functions addressed by the intelligent system. These input/output requirements identify the specific items of information which the human must create and/or input to the intelligent system to allow it to treat the problem, and the items of processed information with which the human must be provided by the intelligent system. The third top-down factor is that of the general human engineering of the man/machine interface. Full application must be made of human factor engineering design principles to insure that the resulting interface is as "usable" as possible. These principles cover such issues as selecting certain display formats on the basis of their general readability or their relative speed of information absorption by operators. There are, of course, many other top-down considerations.

The above three top-down factors, if pursued without regard to the physical constraints of implementation, can easily lead to a design that is completely inappropriate or impractical. (This has already occurred in some prototype "decision aids.") To avoid this, bottom-up considerations such as the three shown in Figure 1 must also be considered. First, the data available on the platform in which the system will operate must be identified. The intelligent algorithm, its man-computer interface, and

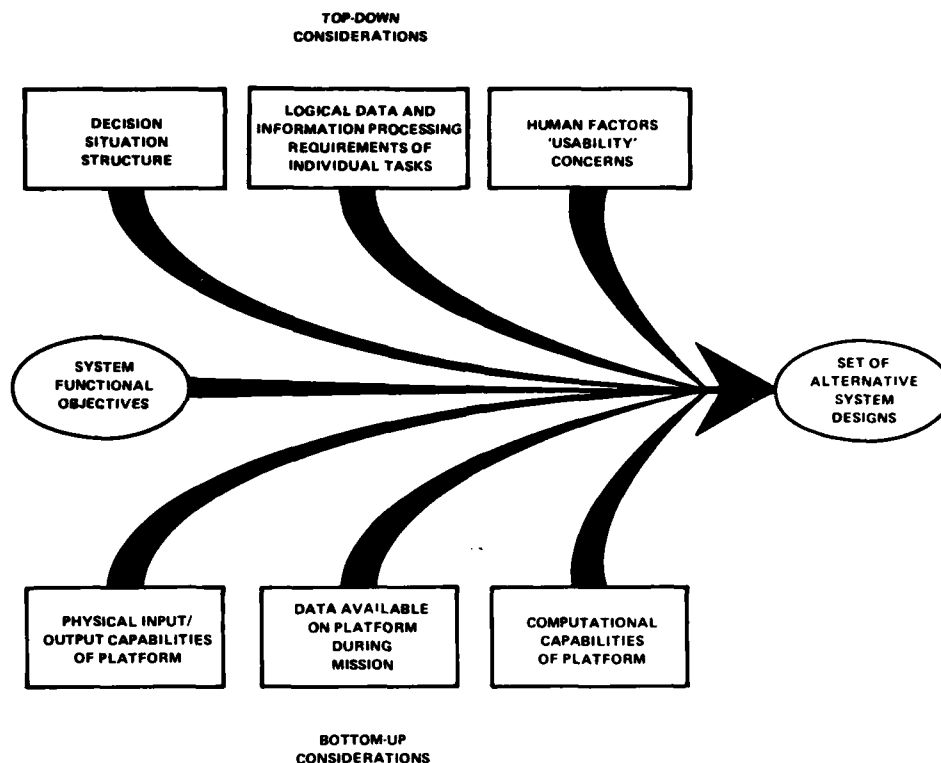


Figure 1. "Top-Down/Bottom-Up" Design Methodology

the human operator must rely strictly upon data which can be obtained on the platform, and must utilize that data in the form in which it can be made available there. The data sources and formats accessible on-board the platform thus define the "working data set" for man-computer pairings. Second, the computational capabilities of the computer processor available on the aircraft must be identified and detailed, as the system must be designed to function within the (decidedly limited) processing capabilities of airborne computers. Third, the physical input and output capabilities of the platform must be identified and used to constrain the input/output possibilities of the man-computer interface. The number and type of display devices available must be determined, along with their respective capabilities -- modes of input, graphic capabilities, display resolution, etc. These devices limit the features which may be built into the man-computer interface for the decision augmentation system, since the interface must operate through these devices. As with the top-down side, there are still other bottom-up considerations which may be relevant. By following both sets of considerations, a workable definition can be obtained of the characteristics of the 'intelligent-system' solution to the operational problem being considered.

Selection of Algorithmic Techniques

Once the characteristics of the solution have been identified, the system designer must then select the mix of techniques which will be used to create a system with those characteristics. For the practitioner, this technique choice must be made at several levels. All computational techniques are obviously not equivalent, as some are directed toward achieving different ends (i.e. perform different functions) than others. The function of certain techniques may be more relevant to certain problems than others, so techniques must be selected according to the functional requirements of that problem. However, some techniques are truly equivalent in that they can be used to exactly the same end. This creates a second level of choice, that of selecting among functionally equivalent techniques. More detailed analysis of this question may reveal even further levels of technique choice. In general, however, the determination of the techniques to be employed in an intelligent system must be based upon a knowledge of the techniques that are available, the capabilities of each technique, and the circumstances or factors which might lead to the choice of some techniques over others as superior in a given situation. Zachary [2] expands on the factors involved in technique selection and provides a preliminary approach to systematic rules for selection.

Evaluation Procedures

Development of symbiotic systems can be both costly (in terms of requiring lengthy development time and expensive implementation efforts) and risky, as there is a danger in not achieving the desired cooperative man-computer partnership and hence

failing to meet the original goal. Therefore, it is necessary to establish and apply objective criteria to assess various design characteristics throughout the design process. This will help eliminate poor or infeasible candidate designs as early as possible and thus minimize the risk in system development. In performing this on-going evaluation process, it is necessary to assess both design feasibility and system effectiveness issues at each stage of the development cycle.

During an early stage of development, it is necessary to perform feasibility evaluations on proposed design alternatives. Computational characteristics of the algorithms to be used in each design alternative must be mapped onto the hardware constraints imposed by the system on which the algorithms will be implemented. It is also necessary to determine whether the algorithmic techniques chosen for each design alternative can meet operational time-constraints (i.e., can the algorithms provide solutions within the time available). These physical performance tests are the first steps in "weeding" the set of candidate designs for the intelligent system.

Another evaluation concern during the early phase of the design cycle is an assessment of whether proposed designs meet the effectiveness criteria. This assessment can be performed by simplified part-task analysis, by analytical modeling procedures, and/or by risk-benefit analyses. The major questions in this evaluation stage are whether the alternative designs can:

- improve the quality of information processing and problem solving, and
- relieve the operator workload to the point the operator is assigned just those problem solving tasks which he can reliably perform.

The emphasis, at this point, is on the word can, as it will only be possible at this early design phase to estimate the potential utility of a candidate design. Its actual performance can not be assessed until something is built.

At later stages in the development cycle, it is necessary to further refine the weeding process and select the single most effective design. Tradeoff studies must be made using simulation software to determine which designs provide the best performance of the intellectual functions required of an intelligent system. The analyses performed here are at a very detailed level, and should employ sophisticated hardware and software simulation. Evaluations of this sort are needed: 1) to assess the viability of the functional allocation between man and computer suggested by each design alternative; 2) to resolve various control/display issues; and 3) to allow resolution of classical cost/performance tradeoff issues. These evaluations will insure an acceptable blend of human and machine information processing capabilities and the greatest likelihood of accomplishment of system objectives. They will also result in specification of a complete system design, down to the finest level of implementation detail. Afterward, when the design is initiated in a high fidelity simulation system, final product effectiveness can be ascertained.

Each step of evaluation during the design of a symbiotic system systematically narrows the set of design candidates which are being considered and methodically refines the level of detail "fixed" in the design of the planned system. This use of constant evaluation increases the likelihood that final design will completely meet its operational requirements and reduces the chances of developing a system which will only marginally perform its intended functions.

The sections that follow illustrate this systematic approach of identifying solution characteristics, selecting algorithmic techniques and evaluating potential solutions. The projects described represent specific design efforts which led to the recognition of the need for the formal techniques and methods for design of intelligent systems described above.

THREE SPECIFIC PROJECTS

This section summarizes three major projects which have been carried out as part of the Decision Augmentation System Program during the last three years. Portions of these three projects were co-sponsored by the United States Office of Naval Research, Engineering Psychology Program. These projects have been neither purely methodological nor purely applications. Rather, each project has concerned a real-world problem in need of a solution via decision augmentation, and has thus served as a crucible for both the development and the application of methodologies for the engineering of intelligent decision augmentation systems. In each case, the specific operational problem being addressed was used as a vehicle to develop a new methodology if no suitable methodology previously existed, or to test the generality of a methodology developed previously in the program. Thus, techniques for identifying required characteristics of solutions, for selecting appropriate augmentation techniques, and for evaluating the feasibility and quality of candidate system designs have been developed for and applied to one specific practical problem, then applied to another and (if necessary) refined and/or expanded to meet that problem's need, then applied to another and (if necessary) refined and/or expanded once again, and so on. In the sense that this application/refinement cycle is still on-going, the methods presented below can be thought of as still in development. However to the extent that they have been successfully applied to several divergent problems, they can be thought of as practical working products.

The three projects discussed below concern the application of decision augmentation to existing crewstations on operational Naval airborne platforms. Two of the studies concern AntiSubmarine Warfare (ASW) platforms, while the third concerns Airborne Early Warning (AEW) aircraft. While none of the studies considered the pilot cockpit directly, it should be clear that the problems considered and solution methodologies derived are as relevant to cockpit design as they are to the tactical crewstations specifically treated.

NAVAL AIR ASW DECISION AIDS

The first major project within the Decision Augmentation Systems Program began in 1978, with the goal of developing systems to aid tactical decision-making on current Naval Air ASW aircraft -- the P-3C and the S-3A --and the soon-to-be-operational LAMPS MK III helicopter. The rapid increase in the technological sophistication in ASW operations in recent years had brought with it a growing demand for quicker and higher-quality decisions on the part of ASW aircrews, and a need was perceived for special systems to augment the decision-making capabilities of tactical crewmembers on ASW platforms.

Initial investigation of the problem showed that the precise roles which these "decision aids" should fill were unclear. There were already a great many programs on board the aircraft's computer which assisted in the processing of specific data. In fact, there were apparently so many that the coordination of their use posed a substantial problem in itself. Thus, we began this project "from the beginning" with an analysis of the commonalities among the missions flown by the principal ASW platforms. This resulted in the construction of a generic Air ASW mission profile, from which the various decisions made during the mission flight by the Tactical Coordinator (TACCO) were identified and investigated. The TACCO was selected as the central focus of this investigation because it is the explicit function of the TACCO to coordinate the decisions and efforts of the other crewmembers into a tactical plan of action to achieve the mission objectives. From the analysis of the generic mission structure, it was found that the TACCO makes similar decisions throughout the Air ASW mission, but toward different ends, depending on the particular objective or goal event of the current mission phase. For example, the TACCO makes sonobuoy (acoustic sensor) placement decisions throughout the mission, but uses different criteria in the segment of the mission where his goal is merely gaining contact with a hostile submarine than he does in the segment where the goal event toward which decision-making is directed is the determination of the submarine's precise location so that an attack may be launched. The differing goal events of the different mission phases were thus found to give rise to complex decision-making contexts, which constrain the way in which the TACCO's primary decision functions are carried out. These contexts, which we termed decision making situations, were identified as the principle units to which decision augmentation should be applied. Six decision situations were defined for Air ASW, and are listed in Table 1, along with their goal events (see [2,3]).

Table 1. ASW Decision Situations and Goal Events

DECISION SITUATION	GOAL EVENT
ON-STATION SEARCH	GAIN CONTACT WITH TARGET OF INTEREST
CONTACT CLASSIFICATION/VERIFICATION	IDENTIFY SOURCE OF CONTACT
LOCALIZATION	DETERMINE LOCATION, COURSE, SPEED AND DEPTH OF TARGET
SURVEILLANCE TRACKING	MAINTAIN LOCALIZED CONTACT WITH TARGET
ATTACK PLANNING	PLACE OPTIMAL ATTACK AGAINST HOSTILE TARGET
LOST CONTACT REACQUISITION	REGAIN AND LOCALIZE CONTACT WITH A LOST TARGET

Having used rather conventional mission analysis techniques to determine where decision augmentation should be applied to Air ASW, the next task was to determine exactly how it should be applied. This, it immediately became clear, required an exact understanding the "state of the art" of decision augmentation. To gain this understanding, we reviewed existing decision "aids" and analyzed them to determine the capabilities and characteristics of current decision aiding technology. To our surprise, complete existing decision aids were found to be highly specialized, and not directly applicable to any of the identified ASW decision situations. In fact, they were found to be applicable only to the (often times artificial) problems for which they were built. However, these existing decision aids were also found to be constructed from similar constituent decision aiding techniques, which proved to be extremely general. Subsequent analysis of the functions these individual techniques played in the various aids showed there were many fewer functional categories of techniques than techniques themselves. We formalized these categories and employed them to group the techniques into a functional

taxonomy of decision augmentation methods, shown here as Table 2. The functional categories around which the taxonomy was built are:

- outcome calculation -- the use of models to predict the outcomes of the current situation, given proposed courses of action,
- value modeling -- the quantitative representation of subjective preferences among possible courses of action to allow precise differences in the desirability of these possible actions to be identified,
- data control/management -- the application of sophisticated mechanisms to facilitate the acquisition, organization, and interrogation of data relevant to the current situation,
- auxiliary analysis -- the manipulation of data and/or relationships relevant to the current situation to provide answers to questions other than the direct prediction of expected outcomes,
- display/data entry -- the utilization of sophisticated methods to transfer data and information from the computer to the human operator and vice versa, and
- human judgement refinement/amplification -- the employment of techniques and models to eliminate bias, error, or inaccuracies in basic human judgments.

Table 2. Taxonomy of Decision Augmentation Techniques

1. OUTCOME CALCULATOR	
1.1	Closed Form Analytic Models
1.2	Probabilistic Models
1.3	Deterministic Simulations
1.3.1	Mechanical
1.3.2	Differential Equation
1.4	Monte-Carlo Simulations
2. VALUE MODEL	
2.1	Multi-Attribute Utility Model (MAUM)
2.2	Adaptively Constructed MAUM
2.3	Direct Assignment of Utilities to Outcomes
2.4	Risk Incorporating Utility Models
2.5	Non-Linear Utility Model
3. DATA CONTROL	
3.1	Automatic Data Aggregation
3.2	Data Management Techniques
4. ANALYSIS	
4.1	Optimization Techniques
4.1.1	Linear Programming
4.1.2	Non-Linear Programming
4.1.3	Dynamic Programming
4.1.4	Fibonacci Search
4.1.5	Response Surface Methodology
4.2	Artificial Intelligence Techniques
4.2.1	Heuristic Search
4.2.2	Bayesian Pattern Recognition
4.3	Sensitivity Analysis
4.4	Intra-Process Analysis
4.5	Information Processing Algorithms
4.6	Status Monitor and Alert
4.7	Statistical Analysis
4.7.1	Distribution Comparison
4.7.2	Regression-Correlation
4.7.3	Discriminant Analysis
4.7.4	Bayesian Updating
5. DISPLAY/DATA ENTRY	
5.1	Display Graphics
5.2	Interactive Graphics
5.3	Windowing
5.4	Speech Synthesis/Recognition
5.5	Quickening
6. HUMAN JUDGMENT REFINEMENT/ AMPLIFICATION	
6.1	Operator-Aided Optimization
6.2	Adaptive Predictions
6.3	Bayesian Updating

The highest-level categories in the taxonomy were used as the basis of a descriptive framework which permits decision situations to be described so that specific relevant decision augmentation techniques can be identified and matched with specific aspects of the situation. This matching methodology was applied to the six ASW decision situations, resulting in an identification of the possible combinations of aiding techniques that are appropriate for each, as shown in Table 3.

Having thus identified the potential applications of decision augmentation in Naval Air ASW, it was then necessary to determine their relative priority, so that development of actual augmentation systems would begin with the highest priority problems. A preliminary attempt at a "pencil-and-paper" prioritization pointed out the need to treat priority as a multidimensional measure, and the need to incorporate the judgments of experienced operational ASW personnel into the prioritization procedure. To that end, a prioritization technique called Priority Mapping was developed and applied to the six Naval Air ASW decision situations identified previously. This technique uses methods known as Multidimensional Scaling and Unfolding Analysis to translate nonquantitative judgments of experienced operational personnel concerning the similarity among, and ranked importance of, decision functions they perform into numerical priority scores for the decision situations in which these decision functions arise. Priority Mapping has three important characteristics. First, it uses the intuition, experience, and knowledge of experienced personnel as the basis for the determination of situational priority for decision augmentation. Second, it uses psychometrically reliable data, in

Table 3. Decision Situations Matched with Decision Aiding Techniques

DECISION SITUATION	DECISION AIDING TECHNIQUES																									
	OUTCOME CALCULATORS		VALUE MODELS		DATA CONTROL	ANALYSIS								DISPLAY/DATA ENTRY				HUMAN JUDGMENT REFINEMENT/AMPLIFICATION								
	CLOSED FORM ANALYTIC MODELS	PROBABILISTIC MODELS	DETERMINISTIC SIMULATIONS	MONTI CARLO SIMULATIONS	MULTIATTRIBUTE UTILITY MODEL (MAUM)	ADAPTIVELY CONSTRUCTED MAUM	DIRECT ASSIGNMENT OF UTILITIES	RISK INCORPORATING UTILITY MODELS	NON LINEAR UTILITY MODELS	AUTOMATIC DATA AGGREGATION	DATA MANAGEMENT TECHNIQUES	OPTIMIZATION TECHNIQUES	ARTIFICIAL INTELLIGENCE TECHNIQUES	SENSITIVITY ANALYSIS	INTRA PROCESS ANALYSIS	INFORMATION PROCESSING ALGORITHMS	STATUS MONITOR AND ALERT	STATISTICAL ANALYSIS	DISPLAY GRAPHICS	INTERACTIVE GRAPHICS	WINDOWING	SPEECH SYNTHESIS/RECOGNITION	QUICKENING	OPERATOR AIDED OPTIMIZATION	ADAPTIVE PREDICTIONS	BAYESIAN UPDATING
ON STATION SEARCH		⊙		⊙	⊙				⊙			⊙		⊙		⊙	⊙		⊙	⊙	⊙	⊙		⊙	⊙	⊙
CONTACT CLASSIFICATION/ VERIFICATION					⊙			⊙			⊙		⊙			⊙		⊙		⊙	⊙			⊙	⊙	⊙
LOCALIZATION		⊙	⊙	⊙	⊙				⊙			⊙		⊙		⊙	⊙		⊙	⊙	⊙			⊙	⊙	⊙
SURVEILLANCE TRACKING		⊙	⊙	⊙						⊙	⊙	⊙		⊙			⊙		⊙	⊙	⊙			⊙	⊙	⊙
ATTACK PLANNING	⊙	⊙	⊙	⊙	⊙	⊙						⊙		⊙					⊙					⊙	⊙	⊙
LOST CONTACT REACQUISITION		⊙		⊙					⊙			⊙		⊙		⊙	⊙		⊙	⊙	⊙			⊙	⊙	⊙

AN UNCIRCLED CHECK INDICATES THE TECHNIQUE IS APPLICABLE TO THAT SITUATION, WITH NO ALTERNATIVE AVAILABLE FOR THAT TECHNIQUE. A CIRCLED CHECK INDICATES THE TECHNIQUE IS APPLICABLE TO THAT SITUATION WITH AT LEAST ONE OTHER TECHNIQUE FROM THE TAXONOMY ALTERNATIVELY APPLICABLE TO THE SAME FUNCTION.

forms of: non-numerical judgements about decision similarity, and simple rank orderings. And third, it produces precise quantitative importance values for each decision function so that the functions may be aggregated across decision situations (see [3,4]).

In Priority Mapping, judgmental (i.e., non-numerical) data on the perceived similarities among a set of decisions are collected with the unconstrained sorting method (also known as the q-sort method) and then preprocessed with an algorithm developed by Burton (see [5]) to obtain numerical measures of the pairwise dissimilarity of these decisions. The method of Multi-Dimensional Scaling or MDS is then applied to this measure of dissimilarity to uncover the principles, or dimensions, that underlie the decisions considered. In MDS, the decisions are represented as points in a multidimensional space -- the precise number of dimensions in the space must be determined as part of the "solution" -- with each dimensional axis representing a fundamental feature or principle which interrelates the decisions (see [6,7]). This intermediate result provides an added bonus, a breakdown of the ASW decision space into its basic dimensions, as perceived by experienced ASW decision makers. Another technique, called Unfolding Analysis, is then applied to the data on the ranked importance of the decisions (collected at the same time as the unconstrained sorting data) and the multidimensional scaling solution to determine the mathematical form of the implicit priority functions used by the TACCOS to rank the decisions. Unfolding Analysis works by seeking a "reference point" in the multidimensional space and a distance metric (formula for computing interpoint distances) such that the order of the distances of the decisions in the space from the reference point replicates the rank orderings (by importance) given by the TACCOS (see [8,9]). When such a reference point and metric are found, the distances of the decisions from the reference point give the decisions' numerical priority scores. The overall prioritization methodology, as applied to Naval Air ASW, is summarized in Figure 2. With straightforward modification, it can be utilized in any environment to prioritize potential decision augmentation applications. Priority scores for the individual decisions were then combined across decision situations in which the individual decisions were embedded, to create a prioritization of the decision situation. These are shown in Table 4. The Priority Mapping analysis was applied twice to order the six decision making situations according to their importance in the two primary types of Naval Air ASW mission (attack and surveillance).

High priority of the decision situation is a necessary condition for the development of a decision aid for it, but it is not a sufficient condition. We realized that it must also be shown that the decision situation being augmented is in fact "aidable" by some candidate decision augmentation system --that there are demonstrated benefits that can be derived from implementing a DAS in the situation. This problem of assessing the potential benefit of a candidate aid is addressed in the current phase of this project.

A candidate high-level DAS consists of a selection of specific techniques from the taxonomy shown in Table 2. This is essentially what results from the procedure of matching the detailed decision description with the taxonomy of decision augmentation techniques indicated in Table 3. A candidate DAS (even at this high level) could produce

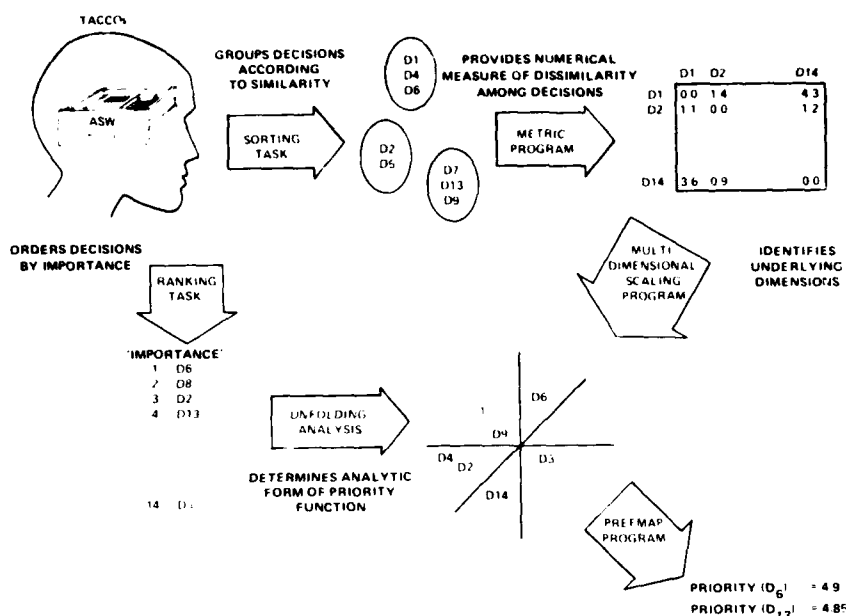


Figure 2. Priority Mapping Procedure for Prioritizing Naval Air ASW Decisions

Table 4. ASW Decision Situation Priorizations in Two Types of ASW Missions

RANK IN MISSION WITH ATTACK OBJECTIVE	DECISION SITUATION	DECISION SITUATION	RANK IN MISSION SURVEILLANCE OBJECTIVE
1	CONTACT CLASSIFICATION/ VERIFICATION	CONTACT CLASSIFICATION/ VERIFICATION	1
2	ATTACK PLANNING	SURVEILLANCE TRACKING	2
3	LOCALIZATION	LOST CONTACT REACQUISITION	3
4	SURVEILLANCE TRACKING	LOCALIZATION	4
5	LOST CONTACT REACQUISITION	ON-STATION SEARCH	5
6	ON-STATION SEARCH	ATTACK PLANNING	6

two kinds of benefits if implemented. First, it could increase the quality of decision making in the specific decisions it addresses and thus directly increase mission achievement. Second, it could decrease the operator workload (both mental and physical) involved with making certain specific decisions and thus indirectly increase mission performance by freeing the operator's capabilities for other concurrent decision making tasks and/or higher-level control and coordination judgments. We found that it was necessary to develop separate techniques for measuring the expected increase in mission achievement and the expected decrease in operator workload. Once developed these techniques could be applied to candidate DAS design for situations identified by Priority Mapping as having high priority.

Increases in mission achievement can be measured in a three step procedure. First, the real-world contingent events which affect the quality of decision-making in the situation being considered, (e.g. the accuracy of intelligence, mechanical/electronics system failures, unanticipated enemy actions) are identified. Second, these contingencies are factorially combined, in the context of a typical scenario mission, to produce a scenario-tree. This is a scenario which can evolve in different ways according to the different combinations of contingent events that may occur. Third, a (mathematical or computer) model of mission achievement is used to calculate the "best" decision that could be made for each combination of contingencies in the scenario-tree. These "best" decisions are assumed to represent the potential quality of augmented decision making, and are compared to the decisions that would be made in the same circumstances using current (baseline) procedures. These comparisons (each the ratio of augmented to baseline performance) are then combined by weighting each particular set of contingencies according to its likelihood of occurrence and then summing the weighted augmented/baseline ratios across all scenarios to produce an expected level of increase in mission achievement.

Decreases in operator workload can be measured in an analogous three step process. First, the current (i.e. unaided) procedures undertaken by the TACCO in making the decisions to be aided are described and formally represented. This formalization is accomplished by using an enhanced version of a task-analytic language called HOPROC.* A corresponding description and formalization is undertaken for the procedures the TACCO would use if the candidate DAS were available. Second, using the same scenario-tree as employed previously, a task/timeline is developed for augmented and baseline procedures in each case. Third, procedures for measuring workload (both mental and physical) are applied to each task/timeline. The augmented and baseline workload measures are then combined across the scenario-tree in the same way as the mission-achievement measures to yield a measure of the expected level of decrease in operator workload. The entire benefit assessment methodology is pictured in Figure 3. A candidate DAS which can show neither type of benefit (higher mission achievement or lower workload) is clearly unwarranted. Conversely, the greater benefits a DAS can exhibit for a high priority function, the more its development is justified.

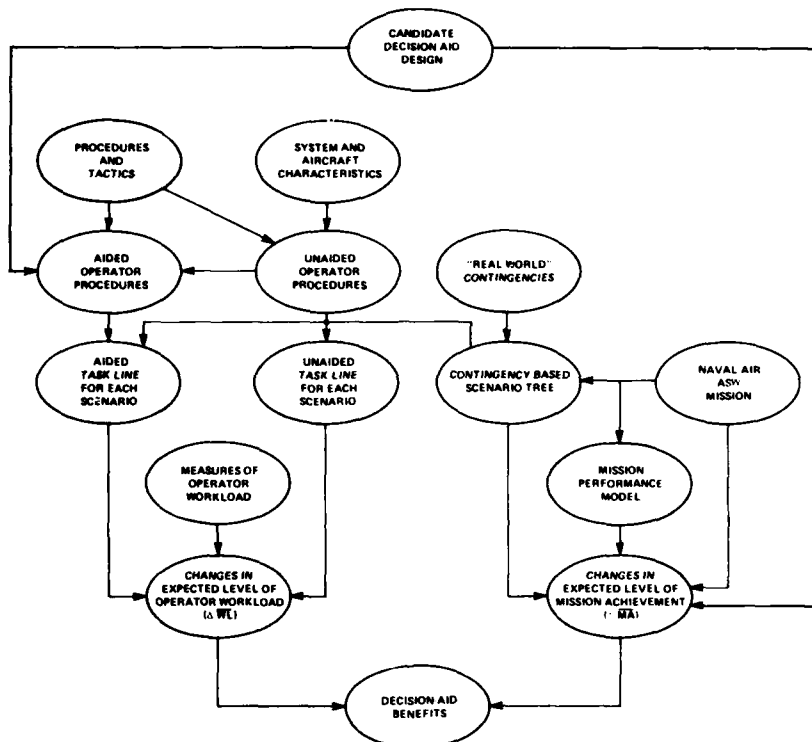


Figure 3. Methodology for Benefit Assessment of Candidate Decision Aids

Benefit assessment has been undertaken for two aids: one for Attack Planning, and one for Sonobuoy Pattern Planning. Results indicate that the Attack Planning aid will decrease TACCO workload and also increase the quality of attack planning decisions, while the Sonobuoy Pattern Planning aid will have minimal or negative impact on workload but will greatly increase the quality of pattern planning. However, any increase in workload by the Sonobuoy Pattern Planning aid will be mitigated by the fact that the aid will be used in portions of the mission where TACCO workload is currently low (see [10]).

The ASW efforts under the DAS project have produced four novel methodological products which are of general applicability. First, they have provided a functional taxonomy of decision augmentation techniques which defines the "off-the-shelf" techniques that can be utilized and combined to produce a complete decision augmentation system [2]. Second, it has developed a method for describing and decomposing decision making situations which results in the identification of precisely the data necessary for the selection of augmentation techniques (from the taxonomy) that are relevant for that specific situation [2,12,13]. Third, it has developed a methodology (Priority Mapping) for the prioritization of decision-making situations for which decision augmentation is being considered [3,4]. And fourth, it has developed an approach to determining whether a given DAS design is likely to result in sufficient benefits to warrant its full development and implementation [10].

*HOPROC is a task-analytic language (see [11]) designed to be used in conjunction with the Human Operator Simulator, a system for digitally simulating human performance.

THE AIRBORNE EARLY WARNING ENGAGEMENT/INTERCEPT PLANNER

The second major project conducted under the Decision Augmentation Systems program has been the development of a true "intelligent system", the AEW Engagement/Intercept Planner. This system is an independent decision automaton intended to function on AEW aircraft in the beyond-1990 time frame. AEW missions in that time frame will demand extremely rapid, precise, and accurate responses to a threat environment expected to consist of waves of high speed aircraft, as well as large numbers of both high and low altitude missiles launched from aircraft, ships, and submarines. The detection and response times for AEW systems will be very limited, and the AEW actions will be critical to fleet defenses. The excessive time constraints on AEW decision-making in such an environment suggested the need for decision augmentation systems in which the computer plays the central role because of its capability for high-speed operations. In this type of system the human plays predominantly a supervisory and/or advisory role. The need for this kind of DAS was reinforced by possible introductions of AEW platforms requiring reductions of current crew sizes without concomitant reductions in mission requirements. This project was undertaken to assess the applicability of the methodologies for problem analysis, technique selection, and system design evaluation (developed in the project described above) to the design of decision automata. Also, because of its narrower focus, this project was undertaken to apply these previously-developed methods to the complete development of a single decision augmentation system.

In the initial stage of this project, the same mission analysis techniques used to model the generic ASW mission were applied to gain an understanding of the AEW mission. As in the previous case, a number of decision situations were identified. These were Sensor Correlation, Threat Detection/ Identification, Target Tracking, Threat Assessment, Engagement/Intercept Planning, and Force Coordination. Of these, Engagement/Intercept Planning was selected for decision augmentation for two main reasons. First, it is difficult for man to perform the tasks necessary for Engagement/Intercept Planning in the current environment, and his ability to perform adequately in the much more complex environment of the future is, at best, questionable. Therefore augmentation will likely be required. Second, this situation is the central tactical problem in the AEW mission, and hence any improvement that can be obtained in this key situation will likely have a direct tactical impact on mission achievement. It should be noted that the Priority Mapping method for prioritizing situations for decision augmentation was found to be inapplicable here, because it relies on the judgements of experienced operators. This feature is normally a great benefit in prioritizing, but the technique's use here was precluded because the proposed tactical environment of the decision automaton was so far in the future and so different from current tactical environment that no useful judgements could be obtained as to the relative similarity/difference of decision functions in it. Thus, we concluded that while Priority Mapping is a powerful method of prioritizing applications for current platforms, it cannot be used for platforms/environments which are not currently in existence or at least in detailed planning stages.

Remaining portions of the methodology developed in the Air ASW study proved to be more applicable to the problem of designing a DAS for the Engagement/Intercept Planning situation. The situation description methodology developed previously was applied to the Engagement/Intercept Planning process to produce a detailed analysis and decomposition of the situation, as shown in Table 5. This situation description was then matched with the augmentation technique taxonomy (Table 2 above), to select the optimal mix of techniques for the decision automaton. The matching proceeded as in the ASW decision situations, except with a different criterion. Techniques from a particular portion of the taxonomy were previously selected as relevant if their application could assist a human decision maker in dealing with the aspect of the decision processing identified by the specific part of the problem description being examined. Now, however, techniques were chosen only if they were capable of autonomously dealing with that part of the problem on their own. The direct result of the matching was selection of a collection of techniques which could address each key aspect of the Engagement/Intercept Planning process. The application of the matching methodology produced an added benefit when applied in this case. The need to treat each key problem aspect could be considered as a separate function in the Engagement/Intercept Planning process. Thus, the matching procedure not only identified techniques to be employed in the decision automaton, it also permitted specification of the function that these techniques would fulfill in the automaton's overall algorithmic structure. In this manner, the selection of specific techniques for use in the automaton also naturally gave rise to a functional block-specification of the automaton's internal structure. This functional structure is shown in Figure 4. The relationships among these functional blocks, the elements in the Decision Augmentation Technique Taxonomy, and the situation description in Table 5 are indicated in Table 6. For each row of Table 6 the first or left-most column shows a selected situational element from Table 5. The second column of Table 6 indicates the general type of function required to treat that situational element. The function types link the high-level categories in the techniques taxonomy with the general aspects of the decision process. The third column in Table 6 specifies the precise technique used to treat the element identified in the first column. Thus, the first three columns summarize the matching procedures. The fourth column in Table 6 identifies the algorithm component (from Figure 4) which will actually utilize the technique in the third column to perform the function.

Development of the actual algorithms for each functional block identified in Figure 4 is currently underway. Also in progress is the development of a methodology for analyzing the requirements of the man/computer interface for this system. The inter-

Table 5. Engagement/Intercept Planning Description

OBJECTIVE: Prepare an engagement/intercept plan for all assets under AEW control.	
UNDERLYING PROCESS: Movement of one or more enemy aircraft toward friendly task force and movement of one or more friendly fighters to intercept and engage them.	
VALUE CRITERIA:	
1. Measure of expected reduction in number of hits on friendly task force.	
2. Measure of increase in $X = \frac{\text{expected number of threats intercepted}}{\text{expected number of friendly aircraft destroyed}}$	
VARIABLES AND PARAMETERS:	
INPUT VARIABLES	PARAMETERS
Track information for all forces.	Intelligence on enemy capabilities:
Hostile track identifications and classifications.	• Weapons types, ranges, capabilities
Threat prioritization of enemy targets.	• Platform types, capabilities
Estimated enemy weapon and fuel status.	• Platform-weapon combinations
EW environment.	• EW capabilities
Electromagnetic propagation conditions.	Intelligence on enemy operations:
Tactical environment.	• Return-to-base considerations
Available friendly-force backup.	• C ³ structure
Atmosphere conditions.	• Projected Rules of Engagement (ROE)
Friendly platform status:	Friendly platform capabilities:
• Weapon systems	• Weapons
• Fuel supply	• Maneuvering
• Non-weapon systems	• EW
	• Man limitations
	Own-force tactics available.
	Current ROE.
DECISION VARIABLES	OUTPUT VARIABLES
Threat time to Task Force BUVAL	Time available for planning and intercept
Time available to plan	Criteria for target allocation
Performance criterion selection	Target allocation with priorities
Assignment of targets to fighters	Intercept tactics for each target
Tactic selection	Initial position or vectors for each intercept
When to engage	Requests for backup forces, especially DLI
Positioning	
Vectoring	
RELEVANT ANALYSES:	
1. Recognition of threat 'cells' that can be handled by a multiple-attack fighter.	
2. Establishment of time and position bounds for enemy action.	
3. Maximization of fighter and other asset utilization consistent with time available and threat priority.	
4. Monitoring of friendly-force status for system failures causing change of plan of action.	
RELEVANT DISPLAYS:	
1. Depiction of "bubble of vulnerability" for task force to each enemy weapon and assignments of targets to fighters with chosen tactics.	
2. Detailed display of single fighter-current target, with all additional information available.	
3. Listing of rules of engagement.	
4. Listing of status of all systems on all friendly fighters.	
5. Listing of requests for backup forces.	
6. Time available to intercept each hostile target.	
REQUIRED HUMAN JUDGMENTS:	
1. Identification of anomalous conditions which will require the human operator to override the algorithm's decision.	
2. Use of special tactics.	
TASK DYNAMICS: Sequential contingent.	

face portion of the Engagement/Intercept Planner poses an especially difficult design problem because the level of the communication it requires far transcends the simple data-transfer level with which most man/computer interfaces are concerned. The decision automaton must be able to communicate abstract concepts to the operator (e.g., its reasoning process and justifications for the actions it recommends) as well as the detailed specifications of the actions taken. While such communication of concepts occurs constantly and naturally between humans, it is only with the advent of true man-machine symbiosis that it must occur between man and computer. Thus, the man-machine interface for these systems raises issues never before addressed in human engineering disciplines (see [14]).

The AEW project has thus far produced three major results [12,15,16]. First it demonstrated the utility of the previously developed problem description and technique selection methods for decision automaton design. Second, it uncovered the ability of the matching procedure to generate functional block specifications for decision automata. And third, it led to the discovery of the special problems of man-computer interfaces which arise in truly intelligent symbiotic systems [14].

ACOUSTIC PERFORMANCE PREDICTION FEASIBILITY

The third major project conducted under the Decision Augmentation Systems program was the feasibility assessment of a proposed comprehensive suite of decision aids for current Naval Air ASW aircraft. This suite of aids was intended to improve performance in the utilization of acoustical sensor information in ASW, and was generically referred to as the Acoustic Performance Prediction decision aid package. We were given

**Table 6. Relationships Between Engagement/Intercept Planning Functional Elements
Appropriate Decision Techniques, and the Generalized Algorithm Components**

FUNCTIONAL ELEMENT	APPROPRIATE TECHNIQUE CATEGORY(s)	APPROPRIATE SPECIFIC TECHNIQUE(s)	GENERALIZED ALGORITHM COMPONENT
MONITOR FRIENDLY SYSTEMS STATUS CELL RECOGNITION	ANALYSIS ANALYSIS	STATUS MONITOR AND ALERT ARTIFICIAL INTELLIGENCE/PATTERN RECOGNITION	ALERTEH 'CELL' RECOGNIZER
THREAT TIME TO BUVAL DETERMINATION TIME AVAILABLE DETERMINATION PERFORMANCE CRITERIA SELECTION	PREDICTIVE ANALYSIS VALUE MODEL	DETERMINISTIC, PROBABALISTIC INFORMATION PROCESSING MAUM NON-LINEAR UTILITY MODEL	A/C MOTION MODEL AVAILABLE TIME ANALYSIS VALUE MODEL
TIME/POSITION BOUNDS FOR ENEMY ACTION DETERMINATION	PREDICTIVE ANALYSIS	DETERMINISTIC, PROBABALISTIC ARTIFICIAL INTELLIGENCE	AIRCRAFT MOTION MODEL LIMITS TO FUTURE A/C LOCATION ANALYSIS
FEASIBLE FIGHTER ASSIGNMENTS WITH FIGHTER VULNERABILITY	PREDICTIVE ANALYSIS	DETERMINISTIC INFORMATION PROCESSING ARTIFICIAL INTELLIGENCE	A/C MOTION MODEL LIMITS TO FUTURE A/C LOCATION ANALYSIS ASSET ASSIGNMENT/ UTILIZATION ANALYSIS VALUE MODEL
EVALUATION OF FEASIBLE FIGHTER ASSIGNMENTS	VALUE MODEL	MAUM NON-LINEAR UTILITY MODEL	
FIGHTER/TARGET ASSIGNMENT WITH TACTIC SELECTION	ANALYSIS	LINEAR PROGRAMMING DYNAMIC PROGRAMMING ARTIFICIAL INTELLIGENCE/ HEURISTIC SEARCH	ASSET ASSIGNMENT/ UTILIZATION ANALYSIS
FIGHTER INTERCEPT TIMING, POSITIONING, AND/OR VECTORING	PREDICTIVE ANALYSIS	DETERMINISTIC, PROBABALISTIC INFORMATION PROCESSING ARTIFICIAL INTELLIGENCE	A/C MOTION MODEL ASSET ASSIGNMENT/ UTILIZATION ANALYSIS
BACKUP FORCES AND OTHER ASSET ASSIGNMENT	PREDICTIVE ANALYSIS	DETERMINISTIC LINEAR PROGRAMMING DYNAMIC PROGRAMMING ARTIFICIAL INTELLIGENCE/ HEURISTIC SEARCH	A/C MOTION MODEL ASSET ASSIGNMENT/ UTILIZATION ANALYSIS
IDENTIFICATION/RECTIFICATION OF ANOMALOUS SITUATIONS	HUMAN JUDGMENT	*	OPERATOR OVERRIDE
USE OF SPECIAL TACTICS	HUMAN JUDGMENT	*	OPERATOR OVERRIDE

* TECHNIQUES NOT SPECIFIED AT THIS TIME

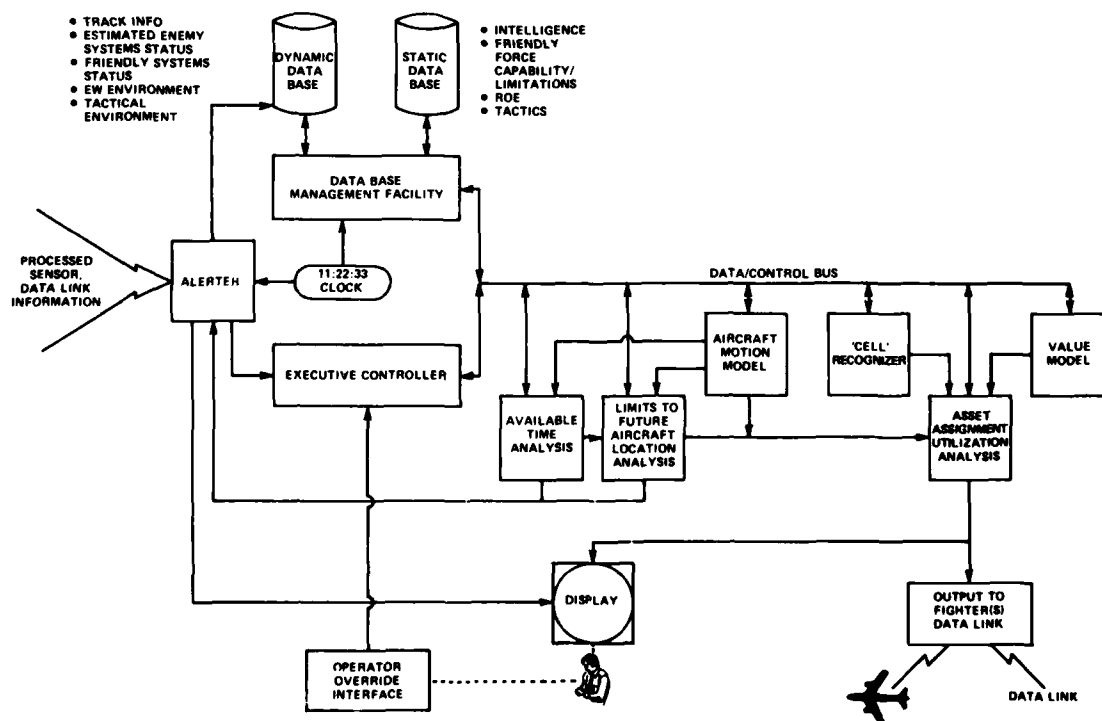


Figure 4. Generalized Engagement/Intercept Planning Algorithm

the opportunity to apply our methodologies (and where necessary develop new ones) to determine the form in which this set of decision aids would have the optimal implementation feasibility in the existing ASW platforms. The range of implementation environments that we could consider was specified as follows:

- implementation in the aircraft's present computer system,
- implementation in the aircraft's present computer system with an added tape-overlay facility, and
- implementation in an added on-board computer dedicated exclusively to decision augmentation processing.

Also specified were the problems which individual decision aids in the complete package would address --search pattern planning, contact investigation pattern planning, localization and surveillance pattern planning, acoustic processor mode selection, passive-to-active acoustic prosecution transition timing, threat assessment and contact classification, multi-sensor signal correlation, and attack planning.

The initial step in determining how a DAS to augment decision-making in these eight problem areas could best be implemented on-board current platforms was to generate high-level design for it. We used the problem description/decomposition methodology which had been so successful in the previous ASW decision aids and AEW decision automaton projects to analyze each of the eight problems and identify the problem aspects which the decision augmentation system design must treat. As in the previous instances, the description method proved completely adequate for the task, and eight problem decomposition tables (similar to that shown in Table 5 for the Engagement planning process) were constructed. Then, using the decision augmentation technique taxonomy and the matching procedure we had developed, we identified the decision augmentation techniques which should be included in the overall DAS suite to treat each aspect of each of the eight problems. Here too, the previously developed method proved completely adequate. The results of this matching provided us with the broad outlines of a DAS whose implementation feasibility we were trying to determine.

The next step was to identify a specific implementation strategy, so that its relative advantages and disadvantages in each of the three candidate environments could be evaluated. This step lead us to consider some of the special characteristics of this type of DAS. It appeared that when a DAS is intended to augment decision-making across a number of problems which are connected by their use of a common data type (such as acoustic sensor information) the DAS could assume a highly modular structure. Each separate problem with which the DAS will deal would require different kinds of augmentation, but because all the problems deal with the same basic type of data, access to the same information will be required for all of them. Moreover, because the data is the same, the same kinds of elementary data manipulation algorithms will also be required for all problems. This meant that each decision aid in the suite could have a different high-level logical structure, but would access the same database and would incorporate many of the same elementary data manipulation algorithms as all the others. For example, all the aids concerned with some type of pattern planning (four of the eight) would require an algorithm to calculate evaluation criterion values for each candidate sensor pattern being considered.

This suggested that the storage requirements for the various aids could be minimized by the use of an implementation strategy which separated the unique components of each aid from those components which could be shared across aids. We defined 18 data modules into which all the information needed by all of the aids could be compartmentalized. We also defined eight generalized processing algorithms which were used in two or more specific aids. These were identified by re-examining the matching of situation description to technique taxonomy, searching for instances where a given technique was found relevant to analogous problem components for two or more descriptions. Thus, at the end of this step we had identified the unique algorithmic components of eight aids in the overall DAS, as well as eight shared algorithmic components, and 18 data modules which could be accessed by any algorithmic component, whether unique or shared.

With this completed, we were then able to estimate directly the amount of storage space required by each unique and shared algorithm component and each data module, as well as the processing resources required to execute each algorithm component. These requirements of the DAS design were then compared to the system capabilities in each of the three possible implementation environments. The impact on other on-board computing functions was also assessed for the first two implementation environments, which required the DAS to share the on-board computer with the existing programs.

Our conclusion was that only a small portion of the overall DAS (e.g., one or two individual aids) could be implemented using just the existing computer system. If a tape-overlay facility was added, then the entire DAS could be added to the P-3C platform only. This is because that aircraft's computer is currently core-constrained, and the tape-overlay would allow its limited core to be effectively multiplexed. In contrast, the S-3A computer is currently CPU-constrained, so that only by adding an additional DAS-dedicated computer could the desired augmentation system be feasibly implemented. With regard to the LAMPS MK III helicopter, it was found that the DAS could be implemented on-board via a dedicated DAS computer, or implemented just as effectively on a ship-board computer, to which the helicopter maintains a constant data link. Of course

in the case of the ship-board implementation the capabilities of the DAS are lost to the LAMPS if the data link is disrupted.

The APP project gave us three major results [17]. First, it has provided still further demonstration that the methods for problem description/decomposition and for augmentation technique selection were valid and robust across a broad range of problems. Second, it led us to discover a powerful strategy for DAS implementation, the use of shareable data and algorithm modules. Third, and most important, it developed a methodology for assessing the implementation feasibility of a given decision augmentation system in the light of real-world constraints. This provided us with the final evaluation tool we needed for DAS design. While we had previously developed methods for determining the impact of a candidate DAS on the operator(s) who will use it, and for determining the improvement in the quality of decision-making that could be expected from a candidate DAS, we had not yet dealt with the important problem of whether an augmentation approach, as embodied in a candidate DAS design, was workable in a given environment. The technique developed in this project gave us a much-needed method to solve that problem.

FUTURE NEEDS AND PROBLEMS

Although gazing into the future is always a risky business, we can nonetheless make what we feel are some "safe bets" as to what will be important in future research and development of intelligent symbiotic man-machine systems. First and foremost, we feel that the need for this type of system will grow dramatically in the near future. The decreasing cost of the computer hardware combined with the increasing demands on human operators will require the machine component of man-machine systems to assume more and more of the intelligence needed to get the job done. Moreover, as the demand for systems of this type grows, the need for techniques to construct them as complete, well-integrated systems will also grow. While we have tried to outline here some of the heuristics which have proven valuable in building complete, well-integrated intelligent systems, we feel that even more concrete guidelines will be needed soon (indeed, if they are not desperately needed already).

Second, we feel that decision augmentation as an important application of intelligent systems technology will continue to grow along the lines that have already emerged. In our research in the area we have employed knowledge and methods from Computer Science, Psychology, Human Factors Engineering, Mathematics, Operations Research, Cognitive Science, Systems Theory, and perhaps other fields as well. Decision augmentation research is thus already strongly inter-disciplinary, and will probably become more so in the future. This is a good trend, as it seems to have produced a kind of "hybrid vigor" that we can only hope will continue.

Third, it appears that the issues of communication between "intelligent man" and "intelligent computer" will take on increasing importance in the future. As intelligent systems of the type we have discussed here move toward widespread application, more and more problems of establishing fruitful communication between the human and computer components of the system are emerging. It is already clear that a dialog between an intelligent human and an intelligent algorithm is a fundamentally different kind of dialog than one between human and a "dumb" piece of software. We know precious little about engineering such intelligent dialogs and until we do, the most fragile piece of symbiotic man-computer systems will continue to be their communications interface.

Finally, we think that the multidisciplinary nature of intelligent systems research in general and decision augmentation research in particular will soon necessitate a great deal of rethinking of the conventional notions of cognition and thought. The current revolution in Cognitive Science has certainly anticipated (and begun) this rethinking, but to the extent that Cognitive Science and Artificial Intelligence continue to focus on intelligent entities (be they men or algorithms) in isolation, their reanalysis will not go far enough. Before we can build truly symbiotic systems we need a much better handle on the ways in which communication mediates intelligence and vice versa; without this, we will be allocating functions to man and machine in the dark, never knowing when a system will fail until it does.

It appears to us that the military aircraft cockpit of the future will include at least two independent intelligences -- the human pilot and the cockpit itself, a network of intelligent computer-based subsystems. Only together, can these two intelligences make the fullest use of the inherent capabilities of each and of the potential of flight as well.

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VISION MONOCULAIRE ET VOL TACTIQUE SUR HELICOPTERE

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RESUME :

L'utilisation de "visuels de casque" pour la conduite des aéronefs entraînera pour les membres de l'équipage, la vision du monde extérieur que d'un seul oeil et avec un champ visuel réduit.

Des enregistrements de la direction du regard à l'aide d'un oculomètre NAC EYE MARKER RECORDER ont été effectués en hélicoptères au cours de missions de type "vol tactique dans les obstacles".

Sept pilotes et trois navigateurs ont été examinés au cours de vingt heures de vol. Chacun des sujets a effectué la mission en ayant pour chaque translation des conditions de vision variables : vision monoculaire ou binoculaire avec champ visuel normal, ou réduit à 60° ou à 40°. Le plan expérimental permet d'avoir pour chaque translation toutes les conditions de vision.

L'analyse du comportement visuel a porté sur la localisation du regard par rapport à l'habitacle et par rapport à la nature de l'objet regardé. Ces localisations ont été traitées en terme de passage du regard d'un objet à un autre ou d'une zone à une autre, en terme de nombre d'arrêt sur les différentes localisations et en terme de durée totale ou moyenne de ces arrêts.

Les résultats montrent que :

1°) pour une condition donnée les sujets se comportent de façon relativement proche les uns des autres.

2°) il existe une modification du comportement en fonction des conditions de vision. Plus le champ est réduit et plus le pilote agrandit son champ d'exploration. D'autre part certaines manoeuvres deviennent difficiles. Pour les navigateurs, le repérage des points importants du terrain devient difficile lorsque la vision se fait en monoculaire et avec 40° de champ.

3°) plus le champ est réduit et plus le pilote regarde près de l'appareil et ses instruments. Les instruments qui deviennent de plus en plus consultés sont les indicateurs de cap, de vitesse et d'altitude.

4°) au cours des vols stationnaires les modifications comportementales sont encore amplifiées par rapport au vol de translation.

5°) la vision monoculaire est plus dégradante du comportement que la réduction de champ visuel.

INTRODUCTION :

Une des caractéristiques du pilotage d'hélicoptère est la prise importante d'informations à l'extérieur. Celle-ci est encore plus nette lorsqu'il s'agit de vols tactiques. Pour que cette prise d'informations se fasse, il est nécessaire de mettre en jeu la vision centrale et la vision périphérique. Or, de nuit, ces systèmes visuels ne permettent pas une perception du monde extérieur compatible avec le vol. Pour pallier cette situation, il faut faire appel à des technologies d'aide à la vision de nuit. Elles sont nombreuses mais seuls deux types paraissent actuellement très intéressants : les jumelles à intensification de lumière et les visuels de casques. Dans ces deux cas, il y a présentation directement à l'oeil du pilote de l'image du monde extérieur et ce quelle que soit la position de la tête. Tous deux se caractérisent par un champ d'observations réduit par rapport au champ du regard du pilote. De même l'image fournie est monochrome.

Les jumelles sont binoculaires et parfaitement asservies aux mouvements de la tête puisque l'ensemble est solidaire de la tête. Le visuel de casque est plus complexe, actuellement monoculaire pour des raisons techniques. Le "senseur" est en outre situé loin du pilote nécessitant donc un système d'asservissement entre la tête et le capteur. Par contre, l'image la plus part du temps d'origine thermique, est présentée sur un tube cathodique fixé sur le casque du pilote donc bien asservi.

Du point de vue psychophysiologique ces systèmes sont assez identiques et se caractérisent par une vision monoculaire ou binoculaire mais toujours avec un champ réduit. C'est cet aspect qui fait l'objet de l'expérimentation ici rapportée.

Cette expérimentation effectuée en collaboration avec les ingénieurs et les opérateurs repose sur l'étude de la direction du regard d'un équipage d'hélicoptère. Cette étude a été entreprise au cours de vols tactiques réels de jour avec simulation de champ visuel réduit en monoculaire ou binoculaire.

1 - MATERIEL, METHODE, PLAN EXPERIMENTAL

1.1. - Le système de simulation de la réduction de champ visuel

Pour simuler une vision du monde extérieur avec champ visuel réduit monoculaire ou binoculaire, le dispositif retenu a été choisi le plus simple possible. Il s'agit de caches en carton munis de fenêtres placées devant les yeux. Ces fenêtres correspondent aux situations suivantes :

- a - sans réduction de champ
- b - vision binoculaire avec champ de 60° pour chaque oeil
- c - vision binoculaire avec champ de 40° pour chaque oeil
- d - vision monoculaire avec champ de 60° pour l'oeil droit
- e - vision monoculaire avec champ de 40° pour l'oeil droit

Le choix de ces champs s'est fait pour se rapprocher des configurations réellement utilisées soit pour les jumelles à intensification de lumière soit pour les dispositifs visuels de casques actuellement à l'étude. La photographie n° 1 montre le dispositif dans la condition vision binoculaire avec champ de 40° pour chaque oeil.

1.2. - Le système d'enregistrement de la direction du regard

Le système utilisé est un oculomètre NAC EYE MARK RECORDER relié à une caméra de télévision AATON, elle-même en liaison avec un magnétoscope à cassette SONY. Ce dispositif représenté sur la photographie n°2 permet de visualiser sur un écran l'image du paysage situé devant le pilote et d'objectiver, grâce à un index lumineux en forme de V, la projection de l'axe du regard sur ce paysage à chaque instant. Le principe de l'appareillage repose sur la propriété du reflet cornéen.

1.3. - Les Tâches

Les différents systèmes de réduction de champ visuel ont été utilisés sur des pilotes effectuant une mission de vol tactique soit comme pilote, soit comme navigateur. Tous ces vols se sont effectués en alouette III le pilote en place droite, le navigateur en place centrale. En place gauche, il y avait un ingénieur d'essais et en place arrière un médecin expérimentateur.

1.3.1. - La tâche de pilotage

Le contexte d'une mission opérationnelle de RENSEIGNEMENTS a été retenu pour définir un profil de vol et des charges de pilotage typiques d'une mission tactique. Cette mission a été décomposée en trois phases de vol :

- a - Progression rapide en vol tactique vers les positions ennemies par bonds successifs d'un point d'observation vers le suivant dès que le compartiment survolé est reconnu sans danger. Cette partie comprend trois bonds successifs.
- b - Observations des positions ennemies par des stationnaires successifs proches, et un vol tactique hors des vues et coups de l'ennemi pour passer d'un point d'observation au suivant. Cette partie comprend trois déplacements.
- c - Au dernier point d'observation une panne ou un coup ennemi est supposé détruire la caméra thermique de pilotage et le pilote doit alors interrompre sa mission et ramener l'hélicoptère à sa base de départ en utilisant la voie infra rouge du viseur de tir. Vol tactique pour sortir de la zone dangereuse puis vol très basse altitude.

1.3.2. - La tâche de navigation

Le navigateur doit trouver des points d'observation à partir de l'étude de la carte et guider sur ces points d'observation. Ces derniers doivent présenter des caractéristiques permettant une observation aisée mais une dissimulation maximum à la vue d'un ennemi.

Deux circuits ont été retenus. Dans le premier, le navigateur a neuf points d'observation à repérer ; dans le second onze points. Il s'agit de circuits présentant les mêmes caractéristiques et le choix de ceux-ci se justifie car les pilotes ont effectué leurs vols sur les deux circuits mais avec des conditions de champs différentes.

1.4. - Les sujets

Il s'agit de sept pilotes tous confirmés et habitués au vol tactique dont l'âge est compris entre 26 ans et 45 ans et qui appartiennent soit au corps des officiers ou à celui des sous-officiers de l'Aviation légère de l'Armée de Terre. La population est donc représentative de celle rencontrée dans les unités.

1.5. - Le plan expérimental

Les sources de variations retenues ont été le champ visuel et la zone de vol survolée. Compte-tenu de l'impossibilité d'utiliser un trop grand nombre d'heures de vol pour cette expérimentation, plusieurs plans différents ont été utilisés par rapport aux sujets. C'est ainsi que pour l'analyse de la fonction pilotage les conditions de champ retenues ont été normales, 60° monoculaire, 40° binoculaire et 40° monoculaire.

Lors de l'étude de la fonction navigation, les mêmes conditions ont été observées, avec en outre un champ de 60° binoculaire. Il faut signaler qu'un délai de six mois existe entre l'expérimentation pilote et l'expérimentation navigateur.

Pour la fonction pilotage, un pilote a effectué 4 fois la mission décrite dans chacune des conditions de champ. Les autres pilotes ont effectué une seule fois cette mission chacun mais avec des conditions de champ différentes pour chacune des translations de points d'observation.

Pour la fonction navigation, il est possible de résumer le plan expérimental retenu dans le schéma suivant :

1° CIRCUIT

	1er Parcours	2ème Parcours	3ème Parcours
1er Navigateur	Normal	40 binoculaire	60 binoculaire
2ème Navigateur	60 binoculaire	Normal	40 binoculaire
3ème Navigateur	40 binoculaire	60 binoculaire	Normal

2° CIRCUIT

	1er Parcours	2ème Parcours	3ème Parcours
1er Navigateur	40 monoculaire	60 monoculaire	Normal
2ème Navigateur	Normal	40 monoculaire	60 monoculaire
4ème Navigateur	Normal	40 binoculaire	40 monoculaire

TABLEAU n° 1 : Plan expérimental. Condition de champ en fonction des parcours pour chaque circuit et pour chaque navigateur.
Pour des raisons de service, le 3ème navigateur a dû être remplacé par un autre dans la 2ème partie de l'expérimentation.

Les navigateurs ont effectué antérieurement la mission en tant que pilote mais ne connaissaient pas les résultats de cette expérimentation.

1.6. - Paramètres mesurés

Pour mener à bien les différents objectifs, deux techniques d'étude ont été retenues. Premièrement, un ingénieur d'essais, établit en temps réel un compte-rendu du vol (hauteur radio sonde, vitesse anémométrique toutes les 30 secondes, réaction du pilote). Deuxièmement, un médecin pratique un enregistrement de la direction du regard du pilote. Cette technique permet d'analyser les mouvements de tête et les déplacements du regard. Ces derniers sont analysés soit en fonction de repères fixes sur l'habitacle (partie centrale ou latérale de l'habitacle, planche de bord) soit en fonction de la nature de l'objet regardé (arbre, champ, habitation, horizon réel).

a) Pour le dépouillement des déplacements du regard

L'habitacle a été divisé en zones particulières représentées sur le schéma ci-dessous. Pour faciliter ce dépouillement, la verrière avait été quadrillée avec un feutre.

La zone 90 correspond au tableau de bord. La zone 30 au pare-brise situé au centre de l'appareil. La zone 20 à la partie inférieure de la verrière avant du pilote en place droite. La 60 à la vitre supérieure latérale droite, la 70 à la vitre inférieure latérale droite. La zone notée de 10 à 16 correspond à la partie supérieure avant droite de la verrière. Elle a été découpée en plusieurs parties car l'essentiel des arrêts du regard se produisent dans cette partie. Les zones 40 et 50 intéressent la partie gauche de l'habitacle. Le pilote en place gauche ne permet pas au pilote en place de voir les fenêtres latérales. Il faut signaler que la zone 10 correspond à la zone où se porte le regard lorsque le pilote regarde droit devant lui, la tête et le corps étant bien droit.

Ce découpage permet donc de savoir où le pilote cherche spatialement ses informations visuelles.

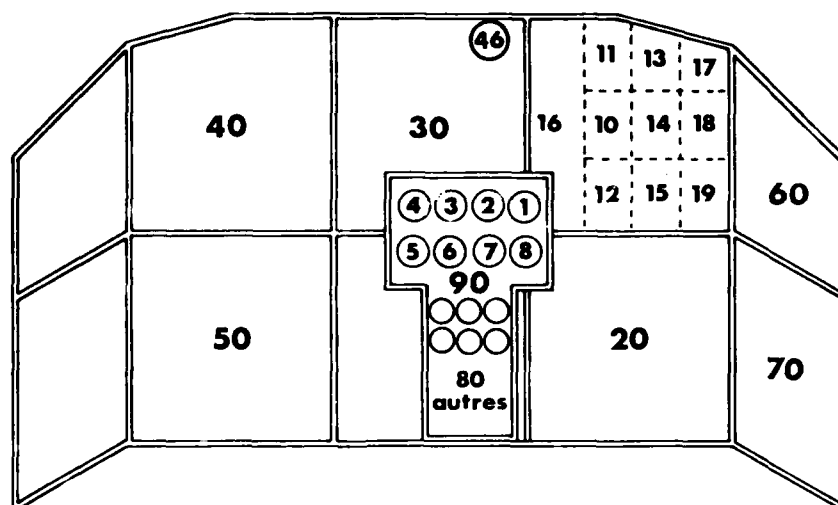


FIGURE n° 2 : Codage en zone de l'habitacle

b) Pour le dépouillement des objets regardés

Un certain nombre d'éléments du paysage ont été codé. Dans ce codage, il a été tenu compte de la distance des objets. C'est ainsi qu'il a été retenu l'horizon sur la ligne de crête (29). Les champs lointains (31), proches (32), les forêts ou bosquets lointains (33), proches (34). Le sommet des arbres (35), la base des arbres (36), le haut d'un piquet ou d'un pylône (37), le bas (38), les habitations lointaines (39), proches (41), les routes ou les fleuves (42) et les véhicules (43). Pour les instruments le code est 01 pour le badin, 02 pour la boule, 03 variomètre, 04 altimètre, 05 radiosonde, 06 radiocompas, 07 conservateur de cap, 08 pas rotor, 09 compte-tours et 80 pour les autres. Le 46 correspond à la boussole située en haut de l'habitacle. L'emplacement des différents instruments est noté sur le schéma n°2. Le schéma n°3 rappelle le codage des objets extérieurs.

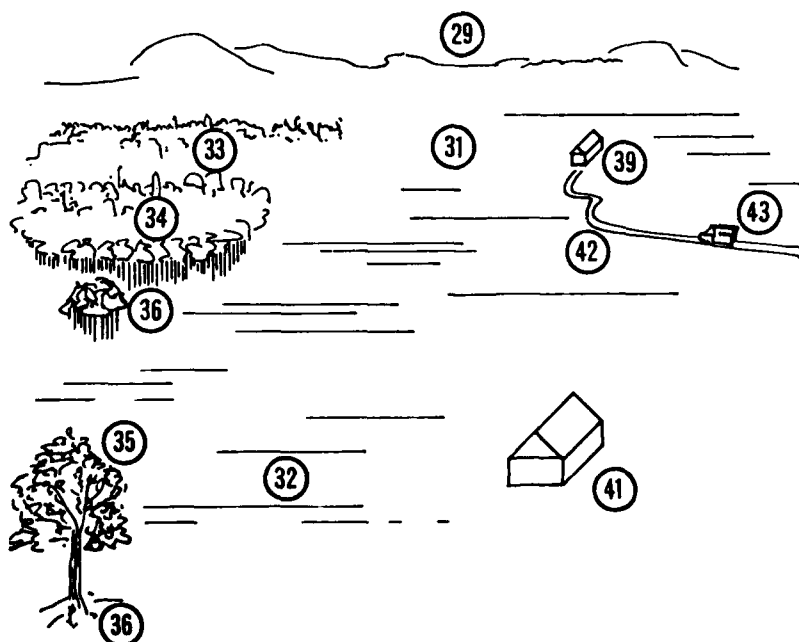


FIGURE n° 3 : Codage des éléments du paysage.

c) Pour le dépouillement de la tâche du navigateur

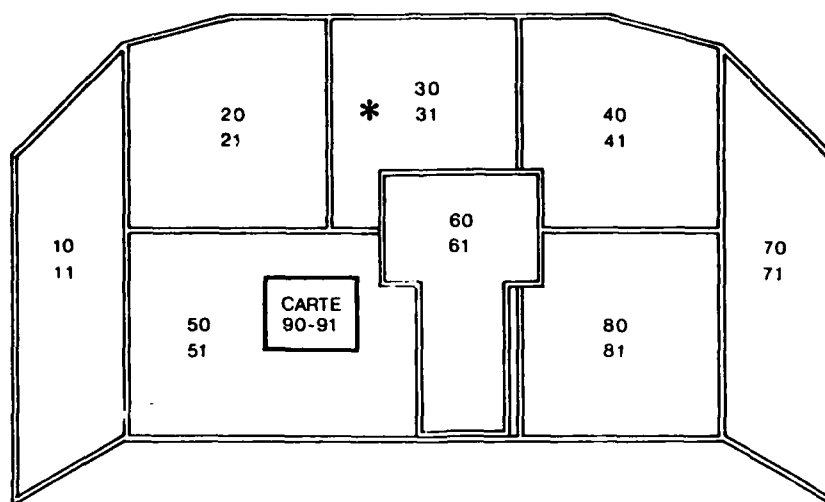


FIGURE n°4 : Codage des zones de localisation du regard pour dépouiller les enregistrements (* indique la position de l'axe du regard lorsque le navigateur regarde droit devant lui).

L'habitacle a été divisé en 8 zones. Pour chaque zone, il y a deux codes. Le premier chiffre de ce code identifie une région donnée de l'habitacle : 1 pour la partie droite de l'appareil, 2 pour la partie située devant le navigateur à droite, 3 la partie située dans l'axe de la machine, 4 pour celle située devant le pilote, 7 pour la partie droite de l'appareil, 5 pour la partie inférieure située devant le navigateur, 6 pour la planche de bord et 8 pour la partie inférieure située devant le pilote. La carte est codée par 9. Le 2ème chiffre permet de décompter les déplacements du regard dans une même zone. On revient alternativement de 0 à 1 et vis versa à chaque déplacement dans une même zone.

1.7. - Technique de dépouillement des déplacements du regard

Le codage décrit ci-dessus permet à un opérateur qui visionne les enregistrements de repérer chaque changement de positions du V lumineux soit par rapport à une localisation de l'habitacle soit par rapport à la nature de l'objet consulté. Ce repérage se fait par une lecture au ralenti des bandes. Un dispositif de dépouillement semi-automatique a été mis au point. Il permet à l'opérateur de n'avoir comme tâche au cours du dépouillement qu'à appuyer sur une touche d'un clavier d'un microprocesseur à chaque fois que le V se positionne sur un nouvel objet ou dans une nouvelle zone. Chaque touche correspond à un objet ou une zone particulière. Cette opération met en mémoire la nature du code utilisée et la durée qui s'est écoulée sur l'enregistrement avant le passage à un nouveau code, ceci quelle que soit la vitesse de défilement de la bande. Les données ainsi stockées peuvent être traitées directement sur ordinateur pour des analyses statistiques.

II - RESULTATS.

Deux sortes de résultats sont exposés ici. Ceux découlant de l'observation en vol et rendant compte de la performance à la tâche, il s'agit de résultats cliniques et ceux intéressant le comportement visuel, il s'agit de résultats traités mathématiquement.

2.1. - Les performances

L'observation directe des sujets au cours du vol et l'analyse de leur réaction après le vol permet de dire que dans presque toutes les configurations de vol le pilotage reste possible quelles que soient les conditions de champ. Cependant, plus le champ est réduit et plus l'appréciation de la hauteur devient difficile, ceci se traduit par une tendance à prendre de l'altitude. Certaines figures de pilotage deviennent délicates et même impossibles à réaliser avec un champ de 40° monoculaire. C'est le cas en particulier d'un "poser" en un point donné après un virage complet autour de ce point. Pour les navigateurs, la tâche leur apparaît de plus en plus difficile à réaliser et il existe un doute croissant quant à l'exactitude des renseignements fournis au fur et à mesure que le champ se rétrécit bien que dans l'ensemble il n'y ait pas d'erreur de jugement.

2.2. - Le comportement visuel

2.2.1. - Des pilotes

2.2.1.1. - En fonction des zones de localisation du regard

Les tests statistiques montrent que tous les sujets se comportent de la même façon. C'est ainsi que le temps passé par le regard dans les différentes zones de localisation est proportionnel au nombre de fois où le regard se porte dans ces zones. Il est donc possible de ne parler que d'un taux de consultations dans les zones de localisation.

Ce taux est variable pour chaque zone et il est possible de hiérarchiser les zones entre-elles. Cette hiérarchisation reste la même quelle que soit la période du vol pour une condition de champ donné. Si, dans l'ensemble, sauf dans le cas 40° monoculaire, la hiérarchisation reste la même (zones 16, 10 et 30 plus regardées que les autres), l'importance relative des taux varie au fur et à mesure de la restriction de champ, les zones périphériques étant de plus en plus consultées et pour le cas du 40° monoculaire presque plus consultées que les zones paracentrales.

Cette variation de comportement est résumée sur la figure n°5.

D'autre part, si, d'une règle générale, quel que soit le champ de vision et quelle que soit la translation, la durée moyenne d'une consultation dans les différentes zones restant de l'ordre de 0,7 à 1,10 seconde (variation non significative statistiquement) dans le cas du 40° monoculaire cette durée moyenne pour la zone 20 c'est-à-dire celle correspondant à la partie basse de l'habitacle atteint la valeur de 1,7 seconde (différence significative).

L'analyse de la stratégie d'exploration c'est-à-dire du passage du regard d'une zone à une autre montre qu'il n'y a pas de différence fondamentale entre les conditions normales, 60° binoculaire et 40° monoculaire, le plus grand nombre de consultations effectuées dans les zones basses font qu'il existe un déplacement de l'importance relative des échanges mais le schéma d'exploration reste le même, c'est-à-dire d'une zone proximale à une autre avec une centration sur les zones 16 et 10 comme cela apparaît sur les figures 6 et 7.

2.2.1.2. - En fonction des éléments du paysage extérieur.

De même que pour la localisation du regard par rapport à l'habitacle, dans le cas du comportement visuel face aux éléments du paysage il n'existe pas de différence en fonction des sujets. Par contre, il existe des variations en fonction des translations. Ces variations sont liées à la nature du terrain survolé (existence de forêts ou non par exemple). Pour analyser un effet lié au champ visuel, les résultats sont comparés sur l'ensemble des vols pour chaque champ. Ces résultats sont présentés sur le tableau suivant :

	Normal	40° Bino	60° Bino	40° Mono
Horizon	10,13	17,95	25,88	1,50
Champ lointain	14,27	8,80	8,76	9,58
Champ proche	22,79	13,32	10,28	44,49
Forêt lointaine	15,47	15,79	19,08	7,70
Forêt proche	9,17	6,86	10,28	3,84
Sommet des arbres	17,83	30,08	17,55	20,39
Base des arbres	6,92	5,82	5,94	10,47
Autres	3,42	1,30	2,23	2,02
Total	100,00	100,00	100,00	100,00
Total des éléments par rapport à "éléments + instruments"	91,96	93,10	92,42	84,52

TABLEAU n°2 : Répartition en % par rapport à la durée totale passée à l'extérieur de l'habitacle par le regard des durées de ce dernier sur les différents objets fonction du champ de vision.

La lecture de ce tableau montre que le comportement est très modifié en 40° monoculaire, l'horizon n'est plus regardé, par contre les éléments à proximité de la machine sont très regardés. Ce résultat confirme le résultat concernant les variations du regard en fonction des zones. En effet, pour regarder les éléments proches de l'appareil, le pilote regarde dans la partie basse de sa verrière. L'analyse de variances sur des durées moyennes ne montre pas d'effet lié au champ la durée moyenne est de l'ordre de 1,1 seconde.

L'analyse des matrices des passages du regard d'un objet à l'autre montre qu'à part les échanges entre sommets et bases des arbres ceux-ci sont aléatoires. Ce qui se comprend puisqu'il y a une exploration liée à des repères géographiques sur l'habitable.

2.2.1.3. - En fonction des instruments de la planche de bord.

De même que pour les résultats précédents, il n'existe pas de différence liée aux sujets, il existe une différence liée à la zone survolée. Il existe plus de consultations d'instruments durant la première période du vol, elle se fait en lisière de bois à flanc de coteaux que durant la deuxième effectuée en colline avec du bocage. La durée des consultations reste proportionnelle au nombre de consultations et les consultations sont plus courtes que pour les éléments du paysage, de l'ordre de 0,5 seconde. Il existe une forte différence de taux de consultations entre les trois conditions normales, 40° binoculaire 60° monoculaire en regard du 40° monoculaire, 7 % ou 8 % du temps contre 15,5 %. D'autre part, la hiérarchisation du taux de consultations sur chaque instrument varie. Ceci est très net sur le tableau n°3.

Instruments	Champs	Normal	40° Bino	60° Mono	40° Mono
Indicateur de vitesse		4,21	2,35	2,85	4,14
Horizon artificiel		1,14	1,33	1,63	1,27
Variomètre		0,76	0,89	0,58	1,36
Altimètre		0,60	0,60	0,65	1,06
Radiosonde		0,12	0,03	0,77	2,15
Radiocompas		0,78	0,03	0,25	1,06
Boussole		0,10	0,43	0,66	2,37
Pas rotor		0,33	0,34	0,11	1,19
Autres		-	0,87	-	0,86
Ensemble des instruments		8,01	6,90	7,58	15,47
Eléments du paysage		91,99	93,10	92,42	84,53

TABLEAU N°3 : Durée relative des consultations sur chaque instrument au cours de l'ensemble des translations, en fonction des différents champs visuels du pilote.

Cette augmentation ne se fait pas de la même façon pour les différents instruments. Elle porte essentiellement sur une augmentation des indicateurs d'altitude (radiosonde, radiocompas altimètre) où elle passe de 1,4 % à 4,3 % de cap. (0,5% à 2,4%). Elle est moins marquée pour le variomètre, elle n'existe pas pour l'horizon artificiel. Le pas rotor est légèrement plus regardé en situation 40° monoculaire. Dans tous les cas, l'indicateur de vitesse est l'information la plus consultée.

Les passages du regard d'un instrument à l'autre se font par proximité pour les instruments mais le plus souvent il s'agit de la consultation d'un seul ou deux instruments en venant de l'extérieur puis retour vers une autre zone de l'extérieur.

2.2.2. - Des navigateurs.

Il existe une variation importante des résultats en fonction des différents champs qui ne s'explique pas par une loi en relation avec la restriction de champ. Les seuls éléments stables sont que les temps passés par le regard sur la carte sont dans tous les cas 2 fois plus longs que les temps passés dans les autres situations (2 s. contre 1,3 s.). Toutes conditions de champ confondues, il apparaît que le navigateur regarde surtout devant lui 50% du nombre des consultations (ceci apparaît sur la figure n°8). D'autre part, il apparaît, comme le montre la figure n°9 que les passages du regard se font de la partie centrale du paysage au côté droit ou gauche et à la carte.

DISCUSSION

L'analyse de la direction du regard sur des pilotes effectuant un vol en vision monoculaire est originale. Une seule étude s'en rapproche : celle de Frezell (2) qui a étudié le comportement visuel d'un pilote monophthalme à la suite d'un accident, au cours d'un vol aux instruments.

Dans le cas de la présente étude, il s'agit de pilotes possédant une vision binoculaire normale. Ceux-ci pilotent occasionnellement et d'ailleurs pour la première fois en vision monoculaire. Dans ces conditions, il apparaît qu'il existe un comportement visuel d'exploration s'organisant spatialement par rapport à l'habitacle. Cette exploration est systématique et se fait d'une zone à une autre zone voisine quelle que soit la fréquence de vol et quel que soit le champ visuel (figures 6 et 7). Cependant, plus le champ visuel est réduit et plus le pilote privilégie une exploration du paysage proche de l'appareil donc spatialement il regarde de plus en plus vers le bas (figure n°5). De même, plus le champ se réduit et plus il consulte les instruments. Cette consultation des instruments varie fortement d'ailleurs avec la nature du terrain survolé. Elle est d'autant plus importante, quel que soit le champ de vision que le relief soit accentué ou qu'il y ait des arbres. La prise d'information à proximité de l'appareil est déjà très marquée en vol stationnaire dès que le champ visuel est réduit à 40° binoculaire au 60° monoculaire alors qu'elle n'est très nette, au cours de translations, que pour le 40° monoculaire. Cette variation de comportement correspond probablement pour le pilote à une nécessité d'avoir des informations qu'habituellement il perçoit en vision périphérique. En effet, en vision sans restriction de champ le pilote explore une zone correspondant à un cône de 30° autour de sa position de repos (figure n°5), ce résultat à d'ailleurs été déjà signalé par Simmons (6) dans ses analyses de la direction du regard en vol tactique. La restriction de champ dans l'expérience rapportée n'est jamais inférieure à ce cône et pourtant le pilote va de plus en plus regarder vers le bas. Par contre, il ne regarde que très rarement vers le haut. La discussion des résultats trouvés avec les pilotes effectuant des vols avec les jumelles à amplification de brillance fait apparaître que le comportement visuel décrit à 40° monoculaire se rapproche du comportement observé en vol de nuit avec les jumelles. En effet, les pilotes disent qu'ils ont tendance à regarder à travers le plancher, c'est-à-dire très près de l'appareil et qu'ils consultent essentiellement comme instruments : l'indicateur de vitesse, d'altitude, de cap et le variomètre. Dans ces conditions, le champ réduit monoculaire de 40° semble être un bon modèle de la vision de nuit mais cette hypothèse demande à être vérifiée par l'analyse objective du comportement visuel de pilotes avec des jumelles et de nuit.

L'analyse des résultats concernant les navigateurs ne permet pas de mettre en évidence un comportement visuel qui varie en fonction d'une loi dépendant de l'importance de la restriction de champ visuel. En particulier, la durée relative passée sur la carte par le regard se situe entre 23% et 30% selon le champ avec des différences qui ne sont pas significatives statistiquement. Ces valeurs s'inscrivent autour de la valeur trouvée par LEWIS et DE LA RIVIERE en 1962 qui signalent un taux d'utilisation de la carte de 28,4%. En ce qui concerne l'organisation de la prise d'information, il apparaît que les échanges se font de la carte vers une des zones face à l'appareil et de là par balayage des différentes zones où de la même zone et retour à la carte. Il y a très peu de balayage sur la carte elle-même peu de consultations de la planche de bord quel que soit le champ. Pourtant, les navigateurs signalent la nécessité de consulter le conservateur de cap lorsque le champ est réduit car ils se désorientent facilement. En fait, ces consultations sont peu fréquentes 1 à 2 minutes de vol. S'il n'est pas possible de mettre en évidence un comportement visuel propre à chaque champ, le vécu de ces situations est très modifié. En effet, les navigateurs trouvent la tâche de plus en plus difficile lorsque le champ se réduit. Ils ont d'autre part une incertitude grandissante de leur "réussite" même si celle-ci reste satisfaisante. Enfin, l'appréciation de la hauteur et des distances est faussée. La comparaison de ces impressions et de ces comportements avec ceux de l'expérimentation effectuée six mois auparavant dans les mêmes conditions sur ces mêmes pilotes exerçant la fonction pilotage, met en évidence que si les impressions restent les mêmes au niveau des difficultés rencontrées, il n'y a pas de doute quant à la réussite mais le comportement varie. Dans le cas du pilotage pour mener à bien la mission de sécurité de l'appareil, il existe une variation du comportement visuel, la stratégie utilisée consiste à regarder de plus en plus vers le bas et à balayer une zone de plus en plus grande au fur et à mesure que le champ se réduit. Ce comportement permet de mener à bien la mission. Il semble donc qu'il s'agisse d'un comportement adaptatif acquis rapidement et spontanément. Dans le cas de la navigation, il n'y a pas apparition d'un comportement adaptatif et il y a un doute quant à la réussite. Il est possible, étant donné qu'il n'existe pas un risque vital si le comportement est inadapté, que le navigateur ne recherche pas spontanément un comportement optimal comme il le fait lorsqu'il pilote. Dans ces conditions, il n'est pas impossible que la tâche de navigation avec champ réduit puisse être améliorée, au niveau du vécu de la situation, s'il est demandé au navigateur d'augmenter son périmètre d'exploration du monde extérieur comme il le fait en pilotant.

CONCLUSIONS

L'état actuel de la technologie des aides à la vision nocturne implique une réduction du champ visuel binoculaire ou monoculaire. Le but de l'expérimentation est d'étudier les modifications de la stratégie de prise d'informations visuelles dans une situation assez proche de celle qui permettent ces aides du type visuel de casque ou jumelles à amplification de brillance.

L'étude de la direction du regard à l'aide d'un oculomètre NAC EYE MARK RECORDER est réalisée lors de vols tactiques de jour sur des pilotes et navigateurs de l'aviation légère de l'Armée de Terre avec simulation de champ visuel réduit (40 à 60°) en monoculaire ou binoculaire.

L'expérimentation montre que pour les pilotes dans des conditions de champ visuel réduit, quelle que soit cette réduction, il existe un comportement visuel d'exploration s'organisant spatialement par rapport à l'habitacle. Cependant, plus le champ visuel est réduit, plus le pilote privilégie l'exploration du paysage proche de l'appareil, donc regarde de plus en plus vers le bas. D'autre part, le regard balaye une zone de plus en plus grande au fur et à mesure de la réduction de champ. De même plus le champ est réduit plus il consulte les instruments.

Pour les navigateurs bien que la carte soit consultée le quart du temps, il n'existe que peu de balayage d'un point à l'autre de celle-ci. En ce qui concerne la vision extérieure, la zone privilégiée est la région frontale. La désorientation devient importante lorsque le champ est réduit ; la tâche alors est trouvée de plus en plus difficile.

En somme, la plus grande partie de ces modifications de la stratégie visuelle peut être rapportée à une nécessité d'obtenir des informations qui habituellement sont perçues en vision périphérique.

Cependant, cette étude ne fait intervenir que les modifications du champ visuel. Avec les systèmes d'aide à la vision nocturne envisagés dans l'avenir, il faut garder à l'esprit que l'image présentée sera différente de ce que voit actuellement le pilote. En effet, il s'agira d'une image construite à partir de l'émission non visible (infra-rouge). Celle-ci à des qualités optiques amoindries.

Ces éléments non pris en compte au cours de cette expérimentation constituent une réserve importante, quant à l'application directe de ces résultats sur de tels systèmes.

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PHOTO 1 : Dispositif de réduction du champ visuel d'un pilote. Cas de la vision binoculaire avec un champ de 40° devant chaque oeil. Sous ce dispositif, il y a le système d'enregistrement de la direction du regard.

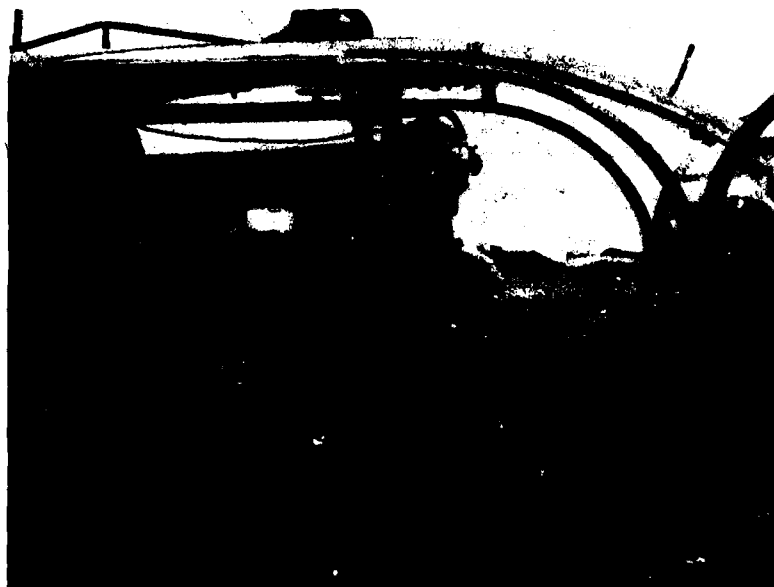


PHOTO 2 : Dispositif d'enregistrement de la direction du regard.

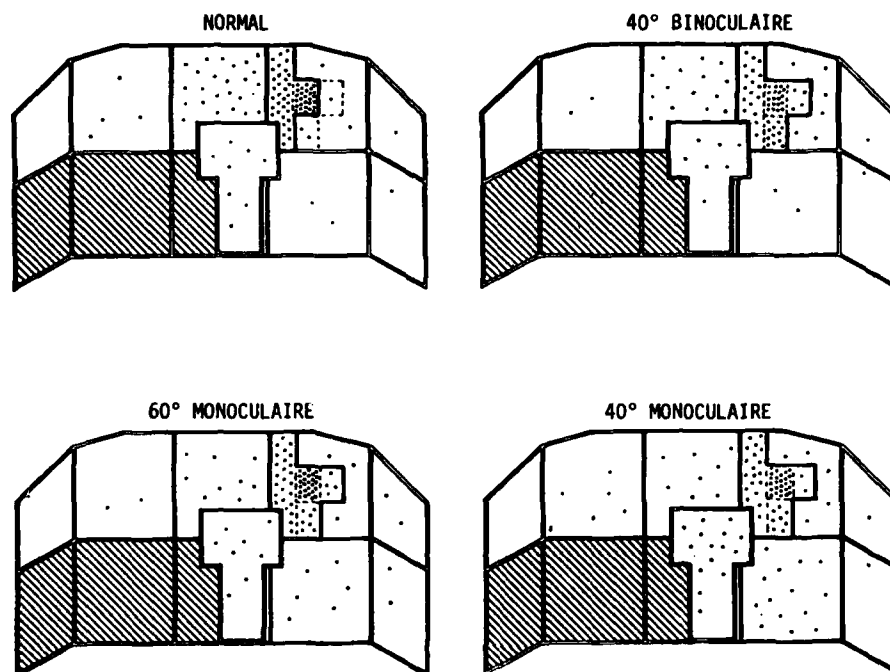


FIGURE n° 5 : Répartition des durées d'arrêt du regard dans les différentes localisations spatiales. L'enveloppe en trait gras correspond pour chaque champ à la surface où le regard reste 80% du temps au cours de la mission. (La zone hachurée n'est pas visible pour le pilote en place droite). (Chaque point représente 1% de durée).

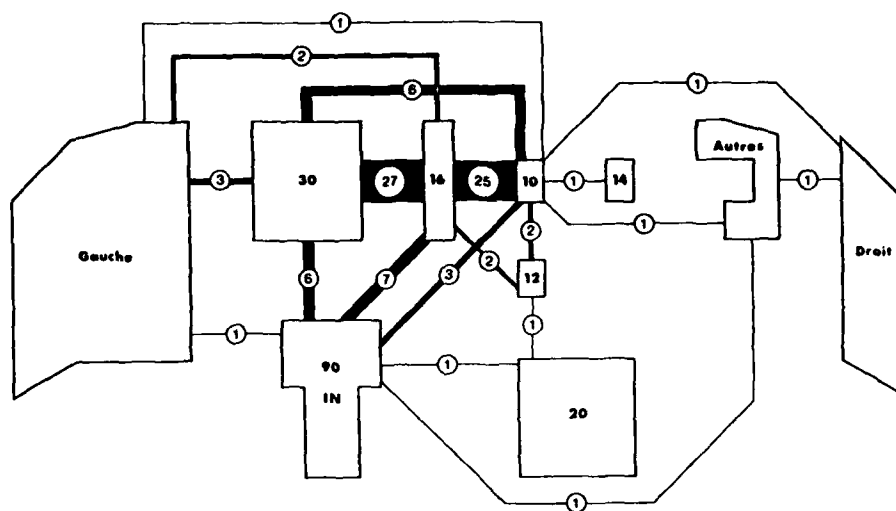


FIGURE n° 6 : % de passages du regard d'une zone à l'autre dans le cas d'un champ normal.

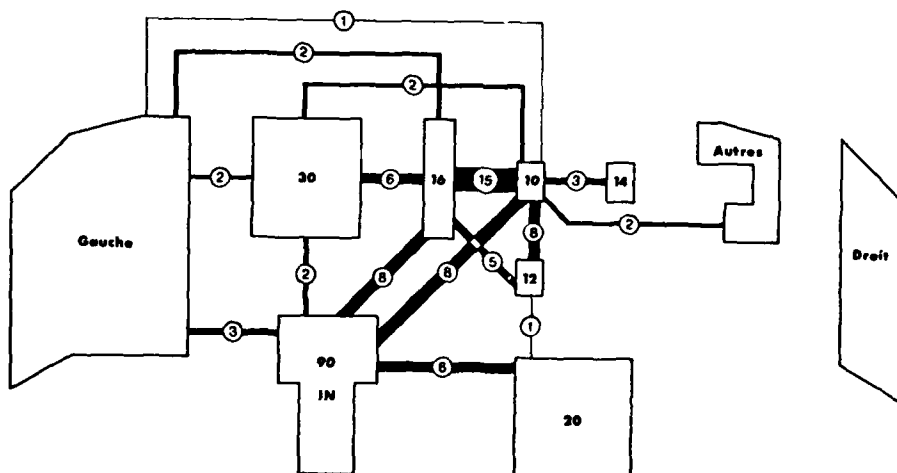


FIGURE n° 7 : % de passages du regard d'une zone à l'autre dans le cas d'un champ de 40° Monoculaire.

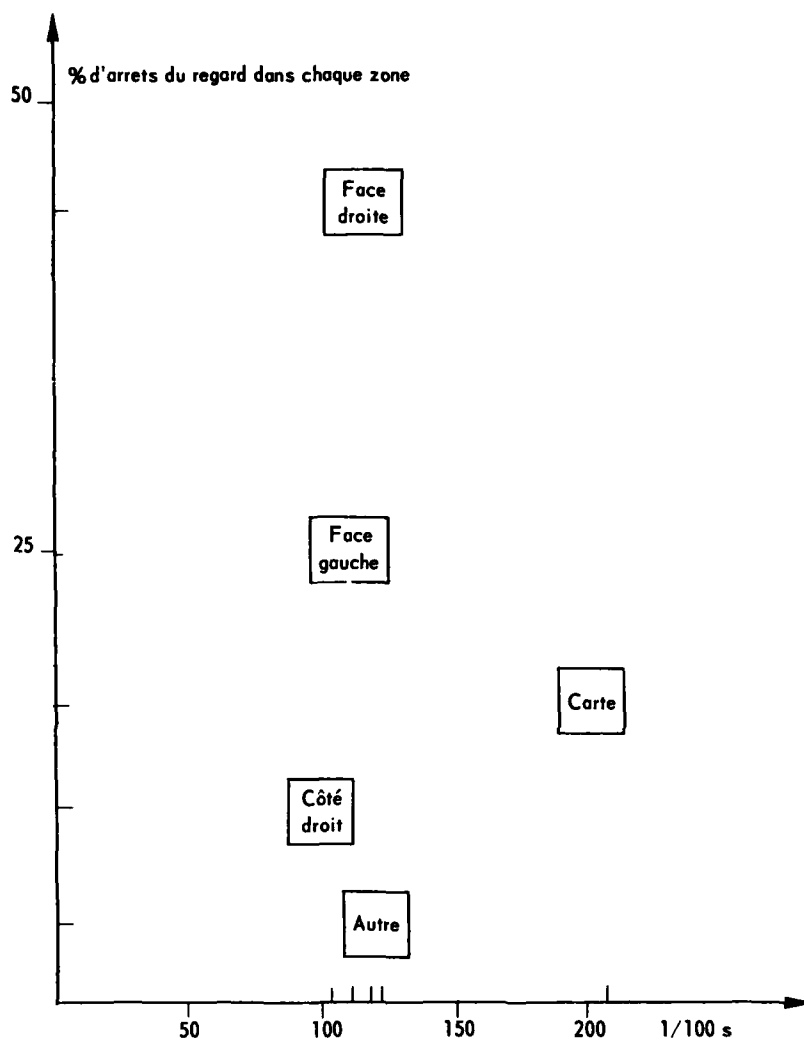


FIGURE N°8 - Pourcentage du nombre des arrêts du regard dans chaque zone de localisation par rapport à la durée moyenne exprimée en 1/100 s.

EXPERIMENTAL INVESTIGATION OF A HELMET MOUNTED SIGHT/DISPLAY FOR HELICOPTER

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SUMMARY

A helmet mounted sight/display (HMS/D) combined with an infrared camera and electronic instrument displays was investigated as a guidance aid for the low level flight of helicopters at night. The static and dynamic accuracy of the tracking mechanism which aligns the lines of sight of both the pilot and the camera was determined by means of a target and motion simulator. System performance was checked with a Bo 105 helicopter in low level flight at night. From the results obtained the importance of the HMS/D as an guidance aid becomes evident relative to other night vision/display systems.

1. INTRODUCTION

The well-known flexibility of helicopter operation is reduced significantly under the conditions of bad weather and darkness. This is because most of the respective missions require the helicopter to be flown at relatively low altitude employing terrestrial navigation as the main guidance aid. Rather than relying on radio frequency, inertial or doppler navigation systems alone the pilot must recognize the structure and very often the fine detail of the terrain ahead, too, in order to maintain orientation and to avoid obstacles. For a more flexible helicopter operation at night one of the most important aspects, therefore, is how the pilot's night vision capability can be enhanced without affecting the ordinary cockpit and flight procedures to an unacceptable extent. Various components as, for example,

- low light level and infrared cameras on a gimbaled platform
- electronic head-up, head-down and helmet mounted display devices
- electronic symbol generators for the generation of instrument displays on the display devices
- night goggles

are available for the specification and for the design of appropriate systems. The question is, however, which combination of these components will serve the requirements of night vision and helicopter guidance in low level flight at night best.

2. OBJECTIVES

In order to study the suitability of these components for future helicopter night vision/display systems the DFVLR Institute for Guidance and Control started a series of experiments some years ago. The order of the components being investigated was largely determined by their respective availability. However, in the mean-time most types of sensors and displays relevant to helicopter night vision/display systems were tested in the laboratory and in-flight and several hundred flight hours were accumulated in Bell UH-1D and Bo 105 helicopters. The tests included ordinary TV/low light level/infrared sensors, a head-down display of sensor and instrument information, night goggles and - last not least - the helmet mounted sight/display (HMS/D).

The objectives of these studies are fairly straight forward and may be classified as follows:

- 1) study the characteristics of various components which may be part of a future helicopter night vision/display system regarding operational requirements, performance and human factors.
- 2) compare the ins and outs of these components relative to each other.
- 3) specify helicopter night vision/display systems for the different modes of application.

In the past the programme of work was directed to reach objectives 1/2 while the present and future activities are focussed on objectives 2/3. The mode of application being investigated in the course of the current programme is "quasi-VFR low level flight" at night. An appropriate combination of terrestrial navigation employing visual aids and artificial navigation aids (RF, inertial, doppler) and/or weapon aiming by means of

night vision/display systems are other modes of application to be investigated next.

In this paper some of the results of an investigation of a helmet mounted sight/display for helicopters are discussed in the light of objective 1) with occasional extensions into objective 2).

3. HMS/D SYSTEM

The system which was investigated is shown schematically in fig. 1. An infrared camera is mounted on a moving platform under the cabin of a Bo 105 helicopter. The image of the terrain is fed to a mixer where it is superimposed by electronically generated instrument displays produced by the electronic symbol generator. The output of the mixer is fed to a helmet mounted cathode ray tube where the combined image is transmitted to the pilot's right eye by means of a semi-reflective mirror. Furthermore the pilot's angular head position is determined by a computer on the basis of the phase relationship between infrared light transmitted from the surveying units and the light received by the helmet sensors. The azimuth and elevation signals are in turn fed to the moving platform in a way that the pilot's line of sight and that of the camera are in close agreement. The camera and the helmet mounted sight/display were provided by HONEYWELL Inc. while the platform, electronic symbol generator and mixer were built at DFVLR. For the laboratory investigations a platform made by DORNIER GmbH was employed, too.

4. TECHNICAL APPROACH

In order to test the static and dynamic accuracy of the tracking mechanism of the helmet mounted sight/display system as shown in fig. 1 the following scenario was employed (fig. 2, 3): The pilot, the HMS/D and the camera fixed to a gimballed platform were accommodated on the moving platform of a moving base flight simulator. The platform was controlled by a computer in pitch and roll in order to simulate the motion of a helicopter.

The platform was surrounded by a rack constituting half of a cylinder with a height of 4 metres and a radius of about 3.5 metres. The rack carried more than 100 incandescent lamps which were controlled in an on/off fashion by means of a computer. The lamps were not distributed uniformly but a number of them was concentrated around the test subject's normal line of sight in order to enhance the resolution in this area. Two lamp control modes could be chosen: For static measurements one particular lamp only was switched on/off while for dynamic measurements adjacent lamps were switched on/off consecutively in order to simulate a moving target. Measurements were made with and without motion of the platform. Different sets of data were obtained for the helmet mounted sight and for the helmet mounted display:

- In the case of the helmet mounted sight the test subjects were able to look at the targets, i.e. the incandescent lights, directly. The image of the camera was not displayed in this case. The line of sight of the camera, however, remained slaved to the test subject's line of sight.
- In the case of the helmet mounted display the test subjects were prevented from looking at the targets directly by means of an opaque visor in front of the helmet. Rather the targets were picked-up by the camera and the resulting image was presented to the test subject's right eye. The line of sight of the camera was slaved again to the test subject's line of sight.

In both cases the test subjects were provided with a reticle projected onto the semi-reflective combiner in front of their right eye. The task was identical for both cases in that the test subjects were asked to align the target with the reticle as efficiently as possible. All tests were conducted in darkness and an ordinary TV camera was utilized for these tests.

The measures of accuracy employed were the angular differences in azimuth and elevation between the test subject's nominal line of sight - given by the straight line from his eye through the center of the reticle to the target - and the line of sight of the camera, respectively. Maximum accuracy was achieved when both lines of sight were centering on the same target.

Flight performance of the HMS/D in combination with an infrared camera (Mini-FLIR, forward looking infrared) was tested in a Bo 105 helicopter (fig. 4, 5). The helicopter is used as a test vehicle for general research on visual aids and displays and is equipped permanently with appropriate systems for process control and data acquisition. This test set-up is supported by display simulation and data processing facilities on the ground. The tests were flown by an experimental pilot wearing the HMS/D. He was assisted by a safety pilot and an observer on the back seat both wearing night goggles.

5. IMPORTANT ASPECTS

All flight tests regarding visual aids and displays for helicopter are flown in an area and over tracks which are identical for most of the experiments. Over the years a knowledge of the terrain and its peculiarities has been accumulated which has turned out to be most useful in order to compare the performance of visual aids and displays and pilot's reaction, respectively, under varying environmental conditions. Important factors are, for example, the structure and the shape of the terrain, visual and thermal contrast between different objects on the ground and between these objects and a low ceiling, the

appearance of streets, railroads, rivers, edges of forests and firebreaks etc. and their effect on flight strategy for the visual aid/display being tested. A relative comparison of visual aids and displays under identical conditions of flight is made possible by this approach and a considerable amount of experience has been gained in this respect in the past regarding head-down and head-up displays, the helmet mounted sight/display and various electro-optical sensors including night goggles.

Another aspect which must be emphasized is the close cooperation with the end-user - the military. Right from the beginning in the mid 70's the sharing of scientific methods on one hand and operational experiences/requirements on the other and a mutual support regarding test vehicles and personnel has led to an efficiency of the research programme which otherwise could not have been achieved.

6. RESULTS

The results obtained from laboratory investigations and flight tests are numerous and they are discussed in detail in the study reports /1, 2/. Therefore, the presentation of results in this paper will be of a more general nature covering some of the most interesting aspects only which may be relevant to the specification of future HMS/D systems.

6.1 Laboratory Tests

a) Display

The display portion of the system was checked first and it was found that the available rectangular display area of approximately 40° diagonal field of view is more than adequate. However, even with a properly adjusted sight/display only 2 test subjects out of 10 were able to see the total display area while on an average only 86 % of the display diagonal could be seen. And because pilots are scanning an area as large as this usually by means of a combination of head and eyeball rotation rather than using eye rotation alone it was found that a comfortable viewing area for instrument displays would be confined to approximately 20° diagonal field of view with a possible small extension into the lower part of the display area (fig. 6). Later in the flight tests it was found, however, that this value may be increased up to 30° diagonal in order to avoid too much clutter of instrument and important terrain information in the center of the display. While quite an amount of instrument displays can be presented in this limited area due to the small line width and excellent focus the image of the sensor may fill the total display area and thereby usefully extend into the pilot's field of peripheral vision.

However, as the image of the infrared sensor had a resolution of 312 lines only its presentation over a field of view of 40° diagonal makes the line structure clearly visible which has a detrimental effect when the quality of the sensor image is less than optimum. This effect can be recognized best when looking through the helmet mounted display itself because photographs, slides, films and video recordings are compressing the image into a field of view in the order of only 10° diagonal giving the illusion of adequate resolution.

The legibility of the display was impaired by a high level of ambient illumination which, of course, was unlikely to occur in the course of these experiments. A standard NATO helmet visor eliminated this effect, however, for levels of illumination of less than 6000 cd/m^2 .

The symbology employed for the instrument displays (fig. 7) - designed for a transport mission - was well accepted in previous flight tests and was considered acceptable for the investigation of the HMS/D system, too. No significant complaints or suggestions were received in this respect.

Because the HMS/D computer provides the pilot's head position in angular terms with reference to the axes of the helicopter, i.e. azimuth, elevation and roll, these signals may be utilized to stabilize the apparent position of the instrument displays in several ways:

- Virtual head-up display

A negative feedback of the azimuth and elevation signals to the position of the instrument displays makes them appear stabilized with respect to the axes of the helicopter. The instrument displays always appear at one particular spot on the windscreen similar to the presentation of a head-up display. However, an uncomfortable feeling of unsteadiness of the display was noticed even when the pilot's head was thought to be at rest.

- Off-axis display

Here the same mechanism as for the virtual head-up display is applied. However, two groups of instrument displays may be formed: one being presented fixed within the pilot's field of view (fundamental HMS/D-mode) and the other being stabilized with reference to the longitudinal axis of the helicopter (off-axis with respect to the pilot's line of sight). A typical off-axis instrument display could be the artificial horizon. Its presentation would become confusing in the fundamental display mode because an indicated bank angle could be interpreted

as a pitch angle if the pilot is looking sideways. The problem would be enhanced further by the apparent disagreement of artificial and natural horizon in this case. A compensation of these errors in the display, however, was considered not desirable with regard to the benefits which can be gained from a stationary attitude indicator and reference system. Furthermore, experiences have shown that in addition to the apparent unsteadiness of the off-axis instrument displays already mentioned the on-axis and off-axis symbols are cluttered fairly often rendering this display mode not very useful. Rather it would be more acceptable to employ the HMS/D-mode, i.e. on-axis symbology, and to switch off those instrument displays which are losing their importance for a sideward view once given limits of head rotation are reached.

- Roll-stabilized display

In the HMS-mode the terrain is seen directly through the optical combiner. It is superimposed by the electronically generated instrument displays. A discrepancy was noted, therefore, between symbols being referenced to the inertial sphere and the terrain when a head rotation in roll occurred. A typical example is the disagreement of the natural and the artificial horizon in this case. A rotation of the head in azimuth always leads to a rotation in roll, too, and the latter was measured to be in a range of up to $\pm 10^\circ$. The roll angle output of the HMS/D computer was utilized, therefore, to stabilize the display with respect to the pilot's head rotation in roll. Although the pilots did not realize that the stabilization was there they reported some discomfort when it was switched off.

b) Tracking accuracy

The tracking accuracy of the complete system comprising the HMS/D and the camera fixed to a gimballed platform was tested in the simulator described earlier (see fig. 2, 3). The controlled variables of these tests were:

- type of application: the system to be used as a helmet mounted sight (camera inoperative, targets could be seen directly) or as a helmet mounted display (targets were seen by means of the camera)
- type of vision: monocular with the eye looking at/through the optical combiner or binocular with the other eye having unrestricted vision
- type of tracking: tracking of stationary or non-stationary targets

Numerous results were obtained and some of more general interest are shown in fig. 8. In this diagram the average angular differences between the test subject's line of sight in demand and the resulting line of sight of the camera are presented in azimuth and elevation together with their standard deviations and the circular error probability (CEP). From the graph on the left side it can be seen that with the helmet mounted sight identical circular error probabilities of 0.35° were obtained for both a centrally located target and for all other targets. The average error did not exceed 0.5° . An almost identical result was obtained with the helmet mounted display for the centrally located target as shown on the right side of the graph. But while the average error still did not exceed 0.5° when other targets were tracked the circular error probability reached a value of 0.83° in this case. Most probably this effect is due to the dynamic response of the HMD-system to a sudden change from one target to another. Here a closed loop is formed by the display presenting the target with reference to the reticle, the test subject, the control mechanism for the gimballed platform and the camera picking-up the target. In the HMS-mode, however, this loop does not exist. The results presented were obtained with the motion system of the moving cockpit flight simulator at rest. System performance is degraded when motion and continuously moving targets are involved [1]. The errors, however, must be analysed individually for each system component including the human operator which is beyond the scope of this paper.

Another factor which affects the tracking accuracy is the effective field of view. A limited field of view only is required in order to track stationary targets but it should be as large as possible to be able to detect/track unstationary and/or moving targets. In the case of the helmet mounted sight more than half of the total field of view is retained for monocular vision due to an overlap of both monocular fields of view and no adverse effects on tracking accuracy were noted in this case. For the helmet mounted display, however, monocular vision is equivalent to looking at the 40° diagonal field of view of the display/camera. This led to less than 50 % of the tracking accuracy obtained for binocular vision in cases where highly dynamic targets were involved.

6.2 Flight Tests.

A transport mission at night was assumed for the flight tests with a demanded altitude of 200 ft agl at 80 kts. The system to be tested as a primary flight instrument (fig. 4, 9) consisted of

- the HMS/D
- the infrared camera fixed to a gimballed platform
- the superimposition of the image of the terrain and instrument information in the helmet mounted display

The ambient temperature was around 0°C and the weather showed occasional rain or snow and a low ceiling. The weather conditions, therefore, were less than optimum for the infrared camera. The shallow viewing angle of the pilot at low altitude and thus of the camera of about -5° with respect to the horizon resulted in a long optical path through areas of high humidity. This contributes to the somewhat adverse but nevertheless realistic environmental conditions. The safety pilot and the cooperating observer were fitted with night goggles (fig. 5).

Again, numerous results were obtained in these tests. In general the pilots were able to fly the mission in demand at altitudes between 100 - 200 ft and speeds between 70 and 90 kts. The data analysis showed that for flights with the HMS/D the helicopter was flown at a higher but more constant barometric altitude and with lower and less variable airspeed in comparison to ordinary VFR-flights. This corresponds well with the observation that the pilots tried to maintain a more constant flight profile by controlling the helicopter in a more gentle rather than abrupt fashion. Nevertheless, the pilots reported higher strain and stress - although acceptable - for flights with the HMS/D with respect to VFR-flights and particularly in comparison to flights employing night goggles. On the other hand they were able to follow a given track with multiple bends (river) very accurately at night which is a demanding task under daylight condition, already. The pilots were able to achieve a fairly constant performance in the course of the experiments. Their visual scanning behaviour was in good agreement with corresponding results obtained from VFR-flights at higher altitudes (200 ft). Performance measures were radio altitude, airspeed, angular motion of the helicopter and their derivatives as well as azimuth and elevation of the pilot's line of sight.

During the tests it became obvious that some system limits were reached sometimes. For example, while the angular response of the moving platform of $25^{\circ}/\text{sec}$ was adequate for a transport mission difficulties were experienced in low level flight at altitudes of less than 100 ft. Higher rates of turn in the order of $100^{\circ}/\text{sec}$ are considered adequate for this flight regime. Furthermore, contrast and resolution of the sensor image need to be increased and a low persistence CTR phosphor would be desirable in order to prevent ghosting of bright targets at high turn rates of the camera. Both features are part of the specification for the new pilot night vision system (PNVS) of the advanced attack helicopter (AAH).

The pilots considered the instrument displays indispensable in order to be able to fly the mission in demand. The display of radio altitude was of particular importance. Although the pilots were complaining that parts of the terrain were obscured by the instrument displays sometimes none of them was considered superfluous.

Due to the relative complexity of the HMS/D the pilot is required to make several adjustments prior to its use. Some of these adjustments can be made on the ground only, e.g. the alignment of the CTR image with the horizon. Other adjustments can be checked by the pilot only, e.g. the visibility of the CTR image. Misadjustments are difficult to detect in-flight, they lead to a reduced system performance and to a corresponding low pilot rating of the system and in one case they resulted in air sickness of the pilot.

Interesting results were obtained in another respect, too. By means of the pilot's line of sight measuring equipment which is an integral part of the HMS/D system the pilot's visual behaviour was analysed with reference to the flight parameters. Fig. 10a shows, for example, the variation of the pilot's line of sight in azimuth as a function of bank angle for low level flight over mountainous terrain. The function gives a quantitative description of the "look-into-the-turn" phenomenon which was difficult to describe in the past. The corresponding frequency distribution of bank angles is presented in fig. 10b. The direction of the pilot's line of sight in the vertical plane is a function of altitude above ground. Up to a height of 200 ft an average depression angle of -4° against the horizon was measured with a standard deviation of 3° . For a height of 200 ft the pilots maintained a depression angle of -5° with a standard deviation of 0.6° .

Finally it was found that the infrared sensor produced excellent to marginal images depending on the weather. More than once a situation occurred where it was difficult if not impossible to discriminate between hills and a low ceiling in the picture. The safety pilot and the observer, however, were able to assess the situation correctly by means of their night goggles.

7. CONCLUSIONS

The conclusions which can be drawn from this investigation may be summarized as follows:

Besides its possible benefits for target acquisition and weapon aiming purposes which were not investigated the HMS/D is a valuable guidance aid. It can provide the pilot with an adequate presentation of information in order to achieve a flexible handling of a helicopter at night. In this respect it is superior to a comparable head-down display of terrain and instrument information. On the other hand system complexity, cost and the reported strain and stress of the pilots are greater than for all other systems tested. This is particularly true in comparison to one of the most promising alternative solutions - the combination of night goggles and an electronic head-down display of instruments for helicopter guidance/navigation at night.

However, for more demanding missions than a transport only and with regard to experiences gained from other flight tests with head-up/head-down displays, night goggles

and various electro-optical sensors it is felt that a single system would be inadequate to satisfy all possible needs. Rather a combination of sensors and displays can be foreseen as an optimum solution. One member of a helicopter crew, for example, could be fitted with a HMS/D linked to a multi-spectral sensor platform for target acquisition and weapon aiming purposes. According to his duties the other crew member may be better off with the provision of night goggles and an electronic head-down display of instruments. Even an alternative use of HMS/D and night goggles was demonstrated successfully (fig. 11). Therefore, investigations like the one presented are considered most valuable for the specification of optimum night vision/display systems without undue preference for a particular component and giving careful and well-balanced consideration to both the operational requirements and the needs of the human operator.

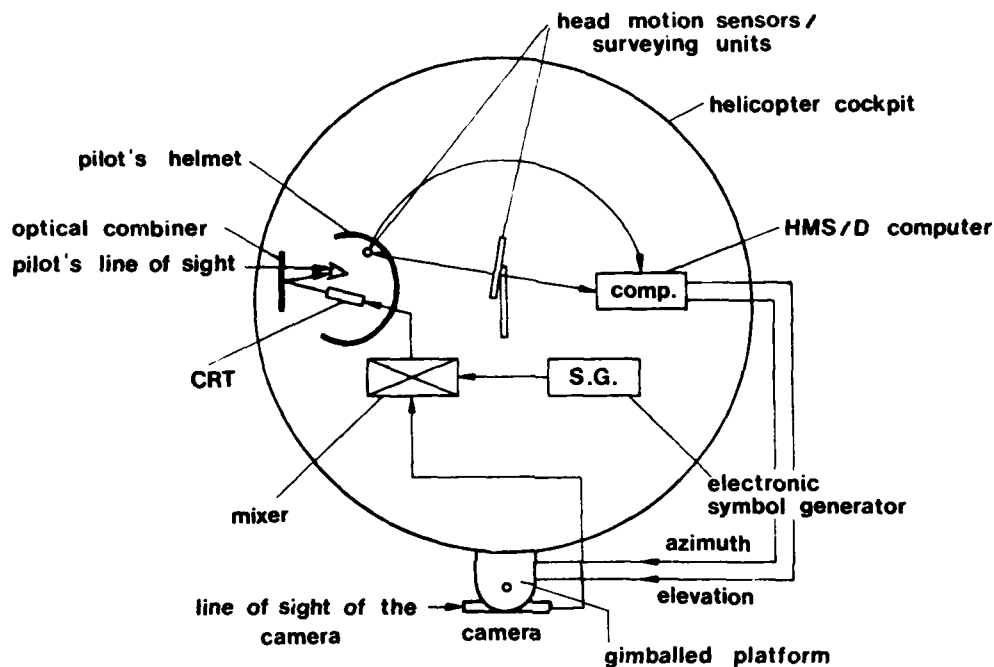


Figure 1: The HMS/D-System.



Figure 2: The moving base flight simulator. The rack carries more than 100 incandescent lamps which are controlled by a computer in order to simulate illuminated targets at night.

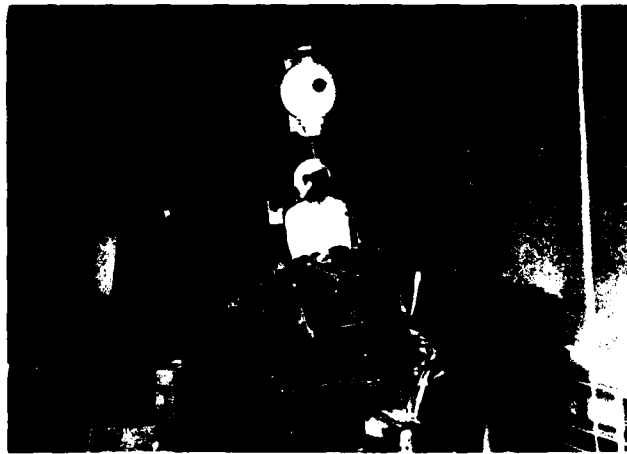


Figure 3: Test subject sitting on the moving base of the flight simulator and wearing the HMS/D. The ball above the test subject's head accommodates the camera.



Figure 4: Bo 105 helicopter with camera fixed to a gimballed platform.

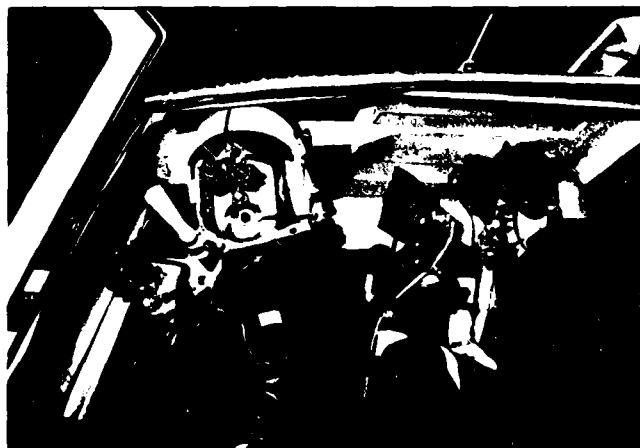


Figure 5: Flight testing of the HMS/D at night. The test pilot is wearing the HMS/D (pulled aside) and additional night goggles for normal flight. The safety pilot and the observer are provided with night goggles for both normal and test flights.

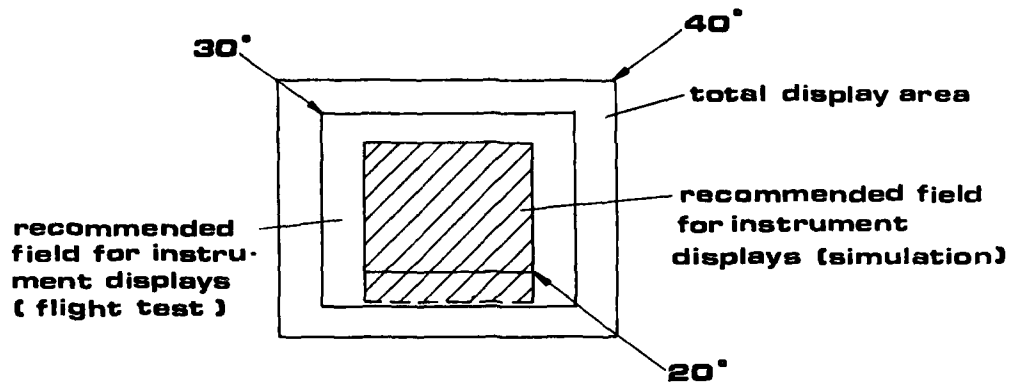


Figure 6: Total display area of the HMS/D and recommended field for the instrument displays.

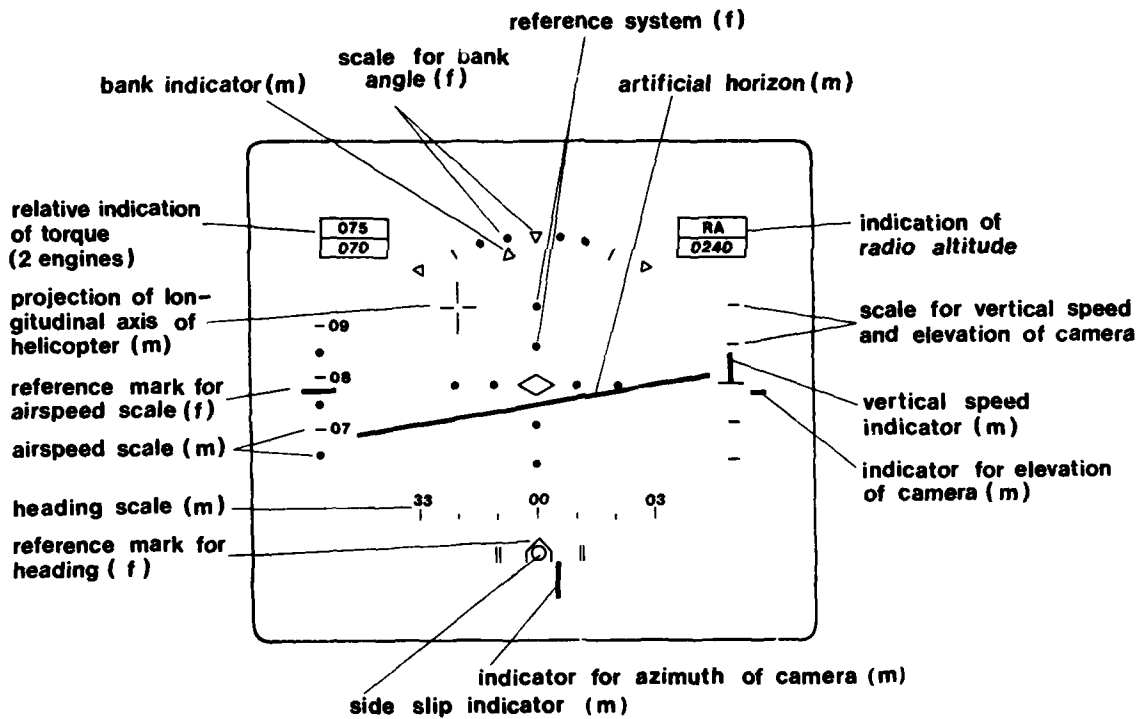


Figure 7: Instrument displays.

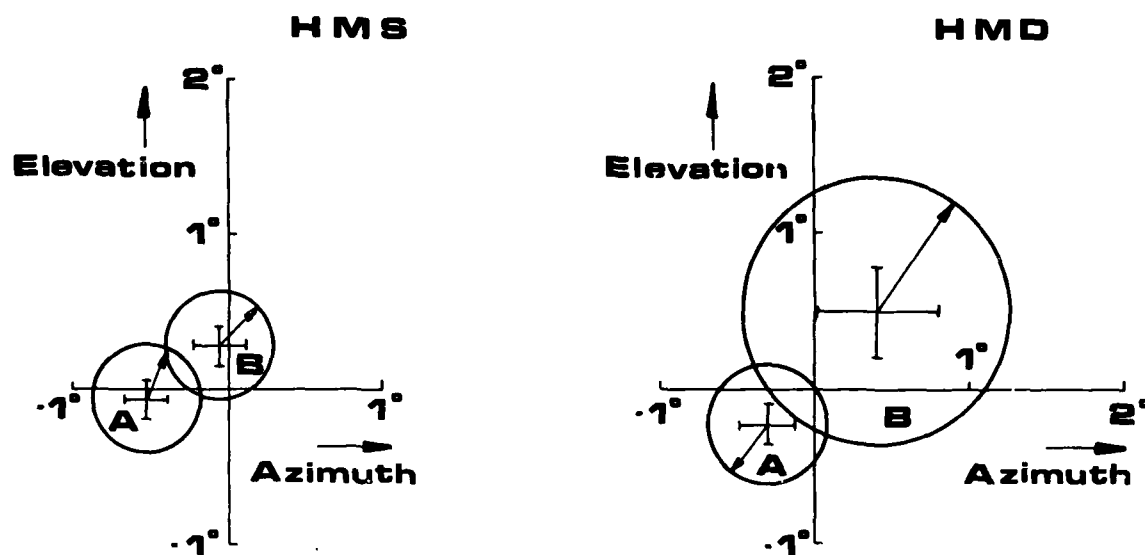


Figure 8: Central error probability (CEP) for the alignment of the helmet mounted sight (HMS) and the helmet mounted display (HMD) with a target.



Figure 9: Pilot wearing helmet mounted sight/display.

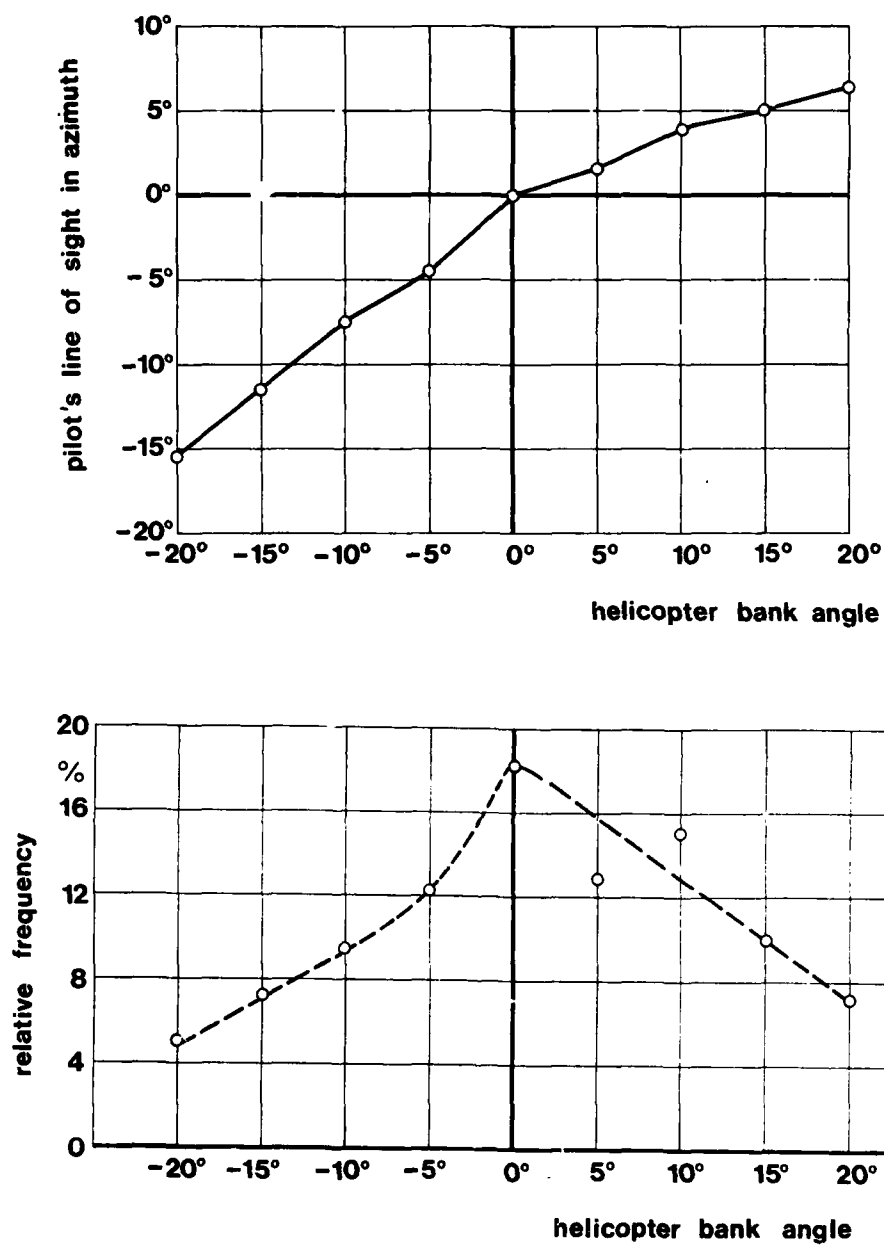


Figure 10: Pilot's line of sight in azimuth relative to the longitudinal axis of the helicopter as a function of helicopter bank angle (a) and frequency distribution of bank angles (b) for flights with ordinary vision and for flights employing the helmet mounted display (HMD).



Figure 11: Alternative utilization of the helmet mounted sight/display (left) and night goggles (right).

USE OF A HELMET-MOUNTED MATRIX DISPLAY FOR PRESENTING ENERGY-MANOEUVRABILITY INFORMATION DURING SIMULATED CLOSE COMBAT

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ABSTRACT

The helmet-mounted matrix display has been developed as a method of presenting information to a combat pilot so that he is not required to glance into the cockpit or at the head-up display. The energy-maneuvrability information gives the aircraft's instantaneous manoeuvring state relative to the structural, aerodynamic and propulsive limits, and should enable a pilot to extract the optimum manoeuvring performance from his aircraft.

Since continuous visual contact with the enemy is essential in close combat the provision of this information on a helmet-mounted source may be particularly useful. However, the (in)visibility of the image against a bright sky background, the increased helmet weight and other inconveniencing counter-effects, when coupled with the high attentional and physical demands of combat, may obviate any advantages of controlling the aircraft using the extra information.

This paper describes the series of exercises set up to assess the HMMD in this application. The device has been the subject of a flight trial in a light jet aircraft, and two studies have been completed in the newly-commissioned RAE Air Combat Simulator. These studies have enabled pilots to become familiar with the device and the unusual display format, before the final study, to assess their combined usefulness in a combat context, is undertaken.

1 INTRODUCTION

The original types of helmet-mounted electro-optical device were the helmet-mounted sight (HMS) and the helmet-mounted display (HMD). The former presented the pilot with a simple image which he used as an aiming mark, whereas the second had a considerably more elaborate optical system to relay the pictorial image from a CRT. Recently, Marconi Avionics suggested that the simple optical system of the HMS could be used to display flight information, weapon firing data, tactical information and warnings, if a miniature matrix of light-emitting diodes (LED) was used as the image source. Such a helmet-mounted matrix display (HMMD) should make information available to a pilot without requiring him to look into the cockpit or at the head-up display, and consequently allow him more time to attend to external events. It was this potential freedom from having to glance into the cockpit, particularly during combat when it was essential to keep the enemy in view and the increased inertial forces discouraged head movements, which has been the principal motive behind the development of the device.

1.1 The matrix display mounted on the RAF Mk 4 helmet

The heart of the display was a miniature square matrix of 32×32 LEDs protruding from the lower rim of an aluminium 'brow-band', which formed the main structural component of the display. The overall device, illustrated in Fig 1, used the brow-band as an enclosure for the hybrid electronic circuits, as a heat-sink, as an optical platform for the matrix, the projection prism and the pair of visors, and as a means of providing vertical adjustment of the optics relative to the helmet shell. This arrangement enabled the device to function as a unit when separated from the helmet shell.

Light emitted from the matrix was collected by the glass prism and directed onto the spherical-section clear visor, where it was reflected into the pilot's right eye so that he saw a clear, bright, collimated image, subtending about 10° diagonally, and having the characteristic red (650 nm) colouration of the LEDs. Although the optical arrangement relied on the image-forming characteristics of an off-axis spherical mirror, the final prism surface was given a cylindrical curvature to minimise the inherent astigmatic aberrations, and the resulting image was adequately sharp and square, as shown in Fig 2.

The original design had specified a high quality moulded polycarbonate inner visor, coated on the inner surface with a dichroic patch for reflecting the red light, but visors made from hot-blown sheet polycarbonate were substituted. These cheaper, but temporary, versions were fitted with coated glass inserts, of the same curvature, and the wearer's right-eyed external vision was partially obstructed by the lower edge of the prism and the joint between this inserted combiner and the clear visor. External vision from his left eye was, however, relatively unrestricted.

Any particular display format was produced by energising the constituent LED elements in rapid succession and was accomplished by transmitting the sequence of element addresses as a BCD pulse-train from a remote electronic unit, called The Matrix Symbol Generator (MSG). This was a microprocessor-controlled data store which also received aircraft parameter signals and performed filtering and scaling calculations. The helmet-mounted electronic components decoded the pulse-train and switched the drive current to the appropriate elements. In the present arrangement an image composed of 100 elements was refreshed 500 times per second, which was certainly adequate to prevent any flickering or spatial disruption which could occur with sequentially activated LED images refreshed at normal television frame rates (Ref 3).

1.2 Previous studies

The initial electro-optical design of the matrix display was first constructed on a simple head-band mounting. This was used to investigate the concept of the device in an air-combat simulation study at BAE (Warton) (Ref 1), and for an assessment of the image legibility under conditions of simulated low-level high-speed flight using the RAE man-carrying vibration rig (Ref 2). These exercises suggested that the

device was useful during combat manoeuvring, particularly as a means of informing the pilot about potential missile-firing opportunities, and that the image remained acceptably visible under high ambient light levels and vibration produced by severe turbulence, providing the image brightness was increased.

Marconi Avionics have also installed the device on US Navy helmets which have undergone flight testing at NATC, Patuxent River, where they were arranged to present energy-maneuvrability information (Ref 4). This study concluded that the information was useful in enabling pilots to become familiar with a new aircraft type and would therefore have advantages for conversion training.

1.3 The assessment plan

The development of the HMD has been encouraged and sponsored by MOD with the primary objective of producing a device in order to assess its usefulness. It was envisaged that the benefits of a helmet-mounted sight for coarse, but rapid, ground target designation, and air-to-air radar cueing and target locking, were sufficiently well established to result in the adoption of a HMS in the near future. Since the HMS required a simple means of projecting the aiming mark in a fixed direction relative to the helmet, it was attractive to consider the benefits of including the matrix image source with its increased information display capacity. The matrix could generate the aiming mark when necessary, but its particular advantage was in providing the flexibility to generate a number of alternative formats, enabling multi-moding, and it could, for instance, depict two-dimensional 'scales' of the energy-maneuvrability variety. However the matrix image source would only be useful if it presented a clearly visible image, if the extra helmet encumbrance was tolerable, and if the information it supplied was relevant and could be assimilated in likely operational conditions.

The studies mentioned in 1.2, addressing specific points of the assessment, have been encouraging. The work reported in this paper is part of the continuing evaluation, and is based on the idea that the physical characteristics of the HMD should be examined in real flight but that the 'informational' aspects would be studied better in the less authentic, but more controllable, conditions provided by simulation. Since the RAE Air Combat Simulator was being commissioned, it was convenient to make use of it, accepting that its newness would limit the nature of the tasks which the pilot could be asked to perform. The contents of this paper are brief summaries of a flight trial, together with two completed simulation studies, the first of which used the HMD to present basic flight parameters and the second involved displaying energy-maneuvrability information in a similar manner to the US Navy and USAF flight trial. The final simulation study, which is currently in progress, is to assess the usefulness of the energy-maneuvrability format in close combat, and the design of this exercise is also reported.

However, before reporting these, it is necessary to introduce and explain the concepts behind the energy-maneuvrability format and also explain why a matrix image source was so suitable for its presentation.

1.4 The energy-maneuvrability format

The basis of the format (Ref 4) is a graphical representation of the aircraft manoeuvring state as the instantaneous combination of load factor (measured by an accelerometer in the z-direction and normally referred to as 'g'), and airspeed (which can be IAS, CAS, TAS, or Mach No.). These two parameters afford a means of delineating the aircraft 'structural', 'lift' and 'thrust' limits, as shown in Fig 3. The structural limit is the load factor at which the airframe is damaged or fatigued, the lift limit occurs at the maximum angle of attack, and the thrust limit is the load factor at which the total drag just equals the maximum engine thrust at a particular airspeed. The flight envelope, contained within the lift and structural limits, is the region in which the aircraft can be controlled safely, and is divided into two areas by the thrust limit. Below the thrust limit an aircraft manoeuvre can be sustained without loss of energy, but above the limit energy loss is inevitable. The shapes of the limiting boundaries are different for different aircraft types and there are also variations for an individual type due to changes in total weight, height, drag changes due to stores carriage, and the deployment of aerodynamic devices such as slats and flaps. In general, the greatest changes occur with height and a high-performance fighter may be limited by structural factors at low level but by aerodynamic and propulsive effects at higher altitude.

Although the diagram provides a very succinct description of an aircraft's performance certain manoeuvring states have greater tactical significance and, by presenting these specific combinations of load factor and airspeed, the diagram can be simplified as shown in Fig 4.

Point X is the stall speed in straight level flight, and it is unlikely that a pilot would wish his airspeed to fall below such a value. Point Q is the intersection of the structural and lift limits which is the condition which results in the maximum *attainable* turn rate. This 'corner' point cannot be maintained in a manoeuvre without a very rapid loss of energy, but point Y, on the thrust boundary, is the condition for obtaining the greatest *sustainable* turn rate.

Very tight sustainable turns, having the minimum turn radius, occur where the thrust and lift limits coincide, at Point W. This usually occurs at comparatively low values of load factor and airspeed, but the aircraft is flown at the maximum angle of attack. Finally, the point Z is the Rutowski airspeed, at which the rate of gain of energy is maximum. The pilot can use this indicator to control the aircraft's angle of climb, at full throttle, so that this airspeed is maintained.

The whole of the image field of view presented on the HMD consists solely of the five points, marking the states of special significance, and a pointer showing the instantaneous combination of load factor and airspeed as illustrated in Fig 5. The axes are not identified, and units and scales are omitted, so that the pilot must be familiar with the significance of each point and the relationship between the instantaneous state indicator and his control actions. In addition to making use of the individual points, the pilot can also interpret the diagram as a rapid indicator of the energy conserving and energy dissipating regions of the flight envelope.

As implemented in the simulation study, load factor ranged from 0 to 8 g in steps of 0.25 g, whilst airspeed was represented by Mach No. and ranged between MO.16 to M1.23 in MO.033 stages. The co-ordinates of the five special points varied only with height, requiring look-up tables in the MSG having 2000 ft steps between sea level and 40000 ft. Organised in this way the display was similar in concept to the arrangement devised by Moroney, Pruitt and Lau (Refs 4 and 5) but it included the extra points showing the stall and Rutowski airspeeds, and it had the benefit of a 32×32 as opposed to a 21×23 element matrix. Other differences were the use of single elements to mark the optimum points, the use of Mach No. rather than CAS, the absence of continuously illuminated elements marking the four corners, and also the absence of the digital height display using the fixed-format elements beneath the smaller matrix.

2 THE FLIGHT ASSESSMENT OF THE HELMET-MOUNTED MATRIX DISPLAY

Since the HMMD would only be useful if it could present a clearly visible image, without hindrance to head movement or normal vision, it was essential to assess the device in a real flight environment. The trial had the primary objective of allowing relevant personnel to experience the device in a range of flight regimes so that they could form opinions about the image brightness, the overall bulk and weight, and the peripheral incursions due to the projection optics. The flights were also arranged to provide subjects with an opportunity to form a more enlightened opinion about the general usefulness of the HMMD for both air-to-air and air-to-ground tasks, and to become aware of the flexibility and limitations of the matrix image source (Ref 6). The information presented was a balance between parameters having possible operational relevance and those which could be obtained from available aircraft sensors. Five formats were arranged:-

- No. 1 Presented airspeed, barometric height and magnetic heading as numbers composed of 5×7 dot-matrix characters.
- No. 2 Contained parameters of relevance for air-to-air use including airspeed, barometric height and fuel as 5×3 dot-matrix character numbers, a vertical angle of attack scale, and a square box to indicate a firing opportunity.
- No. 3 Presented a static energy-maneuvrability format in which airspeed and barometric height were also included.
- No. 4 Contained parameters of likely relevance for air-to-ground use, including airspeed, radio height and heading as 5×3 dot-matrix characters and a central aiming cross.
- No. 5 Illustrated an attack warning, using a large central aircraft-shaped symbol with an inward-pointing arrow indicating the approximate threat direction.

2.1 Equipment

A Morane-Saulnier 760 'Paris' four-seat twin-engined light jet aircraft, owned and operated by the Cranfield Institute of Technology, was the flight vehicle. The aircraft, shown in Fig 6, was capable of aerobatic manoeuvres up to 4 g, and provided a cockpit environment similar to that of a small military jet. The rear left seat was replaced by the MSG, a small tape recorder and an ancillary electronic unit, leaving the front left seat for the CIT test pilot and the two right seats for the subjects wearing the HMMDs. The subject occupying the front right seat also had aircraft controls so that most aircrew could fly and use the HMMD simultaneously.

Five development models of the HMMD were available for the trial. Although they were made to the same notional specification small variations in construction resulted in different functional characteristics. For instance, one of the LED matrices was made from a different batch of gallium arsenide and produced a brighter image (of about 600 nits) than the others (less than 300 nits). The main difference between displays was that they were mounted on three different helmet shell sizes. They were worn with an older type of RAF oxygen mask which differed from the current type by lacking a hard exo-skeleton, but this made little apparent change to the overall helmet stability.

2.2 Procedure

43 subjects participated in the trial. Most were fast jet pilots, two were Army helicopter pilots, one was a navigator and the remainder were engineers, psychologists or ergonomists having a direct interest in airborne displays.

Helmets were fitted to individuals by selecting the most appropriate shell size, and adjusting the internal webbing harness and ear-cup tensions to produce a firm but comfortable fit, with adequate visual clearance at the brow. The clear inner visor was then lowered, the display energised, and the mounting clamp on the helmet crown adjusted so that the subject saw the centre of the image as near to the centre of the inset combiner as possible, as shown in Fig 7.

Following take-off the subject pilot assumed control of the aircraft and had an opportunity to become familiar with its control response whilst climbing to about 15000 ft. The first format was then displayed and both subjects made use of the information whilst looking out. The second format was then selected and the legibility of the smaller numerals and angle of attack scale assessed. The pilot then performed dives, pull-ups, tight banked turns, barrel rolls and loops, to provide an opportunity for assessing the image visibility under increased manoeuvring accelerations and against a background dictated by the changing aircraft attitude and the direction of the sun.

The aircraft was then returned to a height of about 500 ft, but during the descent the energy-maneuvrability format was displayed, enabling subjects to assess the visibility of the image composed of only a few elements. At low level, format No. 4 enabled subjects to practice head aiming whilst monitoring speed and height, and whilst maintaining a look-out. The 5th format occasionally replaced the

air-to-ground information during this phase and the subject's delay in response to the attack warning was noted. During each flight the ambient light levels were measured, and the turbulence induced accelerations were recorded during a few sample flights.

2.3 Results and conclusions

Flying over southern England during August 1980 provided an overcast sky and a fortuitously large variation in ambient brightness ranging from sunlit cloud tops at high altitude at more than 30000 nits, to a ground luminance of about 300 nits below the masking clouds. Although it was anticipated that the display brightness would be inadequate and that the (20% transmission) dark visor would be necessary, most subjects could see the image adequately against low-level cloud, the ground and the blue sky, but they had extreme difficulty perceiving the image against sunlit cloud or within about 30° of the sun, even with the attenuating dark visor.

Fitting the helmets and adjusting the displays so that each subject's right eye was at the centre of the optical exit pupil proved difficult, and either the vertical adjustment was inadequate or the lower edge of the clear visor contacted the oxygen mask. It was also impossible to adjust the direction in which the image appeared relative to the subject's natural 'straight ahead' direction of view, so that a number of subjects found that the image was eccentric within the combiner and displaced downwards.

It was concluded that the device will only be capable of providing a clearly visible and readable image providing the maximum image brightness is increased by a factor of three, if there is more vertical adjustment for the optics and if an independent method of setting the projection direction is incorporated. However, neither normal head movements, aircraft vibration nor manoeuvring forces caused sufficient helmet movement to result in the subjects' eyes being displaced from the device exit pupil.

Visual restrictions due to the brow-band, the prism and the inserted combiner were judged, by about half the aircrew subjects, to be noticeable but not unacceptable in the circumstances provided by the trial. However the aircrew subjects had a justifiable reluctance to have anything attached to their heads which was not essential for their protection or convenience, and some regarded the basic Mk 4 helmet as sufficiently restricting despite its careful design and integration of functions. The extra weight, forward centre of mass, and increased frontal protrusion resulting from the HMMD were noticeable and more tiring on the neck muscles, especially under increased 'g'. These factors, coupled with the reduced head space in operational aircraft cockpits, was considered by most aircrew subjects as making the present HMMD arrangement too unwieldy for operational use.

There was no strong preference for either the 5 x 7 or the 3 x 5 dot-matrix numerals, and most of the digits, scales and pictorial symbols composed of blocks of elements were adequately legible. However, the separated individual elements in the energy-maneuvrability format were particularly difficult to discern against a bright cloud background, and symbols made from small groups of elements were suggested for airborne use. This would require a simple software modification.

Most of the parameters contained in the different formats were considered reasonable and relevant, but detailed modifications were suggested, for instance, to increase the number of significant digits in the airspeed presentation, and to differentiate between radio and barometric height.

Finally, most subjects considered that precise head aiming in turbulence was difficult, but the estimated accuracies accorded with the results from previous trials.

3 THE FIRST SIMULATION: THE COMBAT AIR PATROL TASK

The main potential advantage of the HMMD was to free the pilot from cockpit-mounted information sources, so that he could spend more time looking out. The first simulation study addressed this contention directly by requiring the pilot to fly whilst he searched for airborne targets (Ref 7). The exercise was set in the context of a Combat Air Patrol (CAP) mission in which the aircraft was flown in a closed circuit aligned across the expected direction of approach of an enemy. These 'sentry' missions would normally be carried out in conjunction with other defensive aircraft, which cover neighbouring sections of the front, so that maintaining synchronism was important.

The RAE Air Combat Simulator was set up as a modern lightweight fighter and the essential visual aspects of the task were provided. The pilot's ability to fly at the required height, direction and speed and also to detect target stimuli, could be measured objectively. Since this was the first exercise conducted on the newly commissioned simulator the cockpit lacked most of the conventional instruments and the flying task relied on a head-up display of general flight data, an engine rpm gauge and a stopwatch. Targets were presented, singly, as small randomly-placed low-contrast areas of light on the surrounding spherical screen and they were sufficiently insignificant to require active foveal search rather than peripheral awareness.

The HMMD presented basic speed, height and heading information in a digital format of the same design as used in the initial part of the flight trial. Having been fitted with the helmet, using the procedure described in 2.2, the six subjects were given time to become familiar with the control characteristics of the simulated aircraft, the appearance of the targets, use of the HMMD, and the task of flying around the CAP circuit. Each subject flew five consecutive circuits with the aid of the HMMD and five with the display image blanked. Three subjects received the HMMD-aided condition after flying with the image blanked so that order effects were balanced over all subjects.

3.1 Results and conclusions

Pilots' comments reinforced their opinions from the flight trial. The increased helmet weight and forward protrusion introduced small inconveniences to their normal vision and head movements, with a noticeable incursion due to the boundary between the inset combiner and the clear visor. The display image was also found to be positioned too low in their natural forward view, and most attempted to

counteract this using an unnaturally high head posture. The image was of acceptable quality and the information could be assimilated easily.

The most relevant and virtually unanimous opinion was that the availability of the HMMD information made little difference to the manner in which the pilots performed the task. Five of the six relied solely on the HUD, finding this information more easy to use and more comprehensive. It was considered to be more convenient to include all the HUD information, the timing, and engine rpm data in a scan, and ignore the HMMD. The idea of using the HMMD image as a quick indication of the aircraft state was not attractive, because the digital presentation made it difficult to assess the rate at which the aircraft was departing from the required flight parameters.

These subjective conclusions were reinforced by the objective performance measurements shown in Fig 8, which gives the joint performance of each subject for the 'flying' and 'detection' tasks, on graphical axes arranged so that improved searching moves a point upwards and an increase in flying accuracy moves a point to the right. Target detection performance was assessed from the number of targets detected, and the flying accuracy was the average deviation of height, speed and heading from the required values expressed as a percentage of the allowable errors. This method of describing the combined task performance indicates that the largest variation in performance arose from differences between subjects, largely because they applied different priorities to the two component tasks. The effect of the availability of the HMMD information was to introduce small improvements to the combined task performance for some subjects, an apparent change in the trade-off between the two tasks for others and a small decrement for the rest. Comparing the mean level of combined performance over all subjects for the two conditions shows negligible change due to the availability of the HMMD image.

This result may, however, be due to the paucity of visual cues, and the absence of kinaesthetic cues to assist in controlling the simulated aircraft, which combined with the comparatively exacting flying performance, produced an exercise with an unlikely mixture of precise 'instrument flying' and a visual external search.

4 THE SECOND SIMULATION: THE MANOEUVRE SEQUENCE

This exercise was arranged so that subjects could become familiar with the energy-maneuvrability format and so that the implementation of the format could be checked prior to the main exercise. It also provided an opportunity to assess whether the comparatively novel form of presentation could be assimilated, and whether it enabled a pilot to extract improved performance from an aircraft (Ref 8). The pilot's task consisted of flying a sequence of five manoeuvres which demanded that the aircraft be flown to its appropriate limit. The usefulness of the energy-maneuvrability information could then be assessed from any decrease in the time taken to complete the manoeuvre sequence.

The simulator behaved as a modern lightweight fighter in which the main flight information was presented on the head-up display and an additional cockpit-mounted 'g' meter. There was no interaction with a target aircraft and the main external visual cue was the horizon, separating the blue sky and brown ground, projected onto the inner dome surface.

The sequence began at low level and slow speed, the first manoeuvre being a horizontal turn through 360° which lead into (No.2) a climb to 20000 ft. Having attained this height the pilot performed, (No.3) a horizontal turn through 180° , (No.4) a dive down to 1000 ft and finally, (No.5) a loop, ending straight and level. The eight pilots were allowed adequate time to become familiar with flying the simulated aircraft at its limits and the behaviour of the energy-maneuvrability display. They also practised the manoeuvre sequence, both with and without the use of the HMMD information. The first two subjects were asked to fly to an accuracy of ± 250 ft in height and ± 5 deg in heading, but these demands were relaxed to ± 1000 ft and ± 10 deg for the remaining six subjects so that they could allocate more attention to the control of speed and load factor, rather than be preoccupied by the accuracy of the flight path. Each pilot completed the sequence six times and during three of the runs the HMMD was active, alternating with three others in which only the HUD and the 'g'-meter were available. The sequence was reversed for half the subjects to avoid ordering effects. Operation of the simulator was monitored using a monochromatic split-screen video presentation in which the HUD information, the HMMD format and an overhead view of the pilot were combined, as shown in Fig 9. The signal was recorded as a means of carrying out subsequent assessments.

4.1 Results and conclusions

The energy-maneuvrability format was visible, readable and understood by all the subjects, although some blurring and miss-focussing was apparent. It was also considered to be relatively easy to switch attention between the HUD image and the HMMD image, all pilots preferring to position the HMMD image very close to the HUD field. Only one subject reported any difficulty interpreting the significance of the individual points, and that was due to head tilts, which rotated the image. Two subjects became temporarily unsure of the significance of a point when it was overlaid by the aircraft state symbol. Most subjects reported considerable confusion when the airspeed or load factor temporarily exceeded the available range causing the state symbol to disappear off-scale. They favoured limiting the allowable excursion so that the symbol remained within the field of view, but reducing the number of elements making up the symbol to indicate that the appropriate parameter was beyond the scale limits. All of the subjects thought that the presentation of a complete line diagram, rather than the five optimum points, would be unnecessarily cluttered.

4.1.1 The 360° turn

Most of the pilots used the energy-maneuvrability information, when available, to accelerate to the airspeed at which the aircraft could sustain the maximum turn rate, and then to hold the sustainable load factor. They also had to control the aircraft height, primarily using the vertical speed scale on the HUD, and terminate the turn at the appropriate heading, so it was necessary to transfer attention

between the two information sources. Some pilots preferred to ignore the HMMD image, and use the HUD and the 'g'-meter for all the runs.

Analysis of the times taken to complete the turn suggests that the large range of times (± 8 s in a mean of 44 s) were mainly due to a variation between subjects and that the 1 s average extra time for runs completed with the HMMD image available, was statistically insignificant.

4.1.2 The climb

Only two pilots found the energy-maneuvrability data helpful for this manoeuvre. They were able to adjust the angle of climb so that their airspeed followed the Rutowski value, with occasional glances at the height and heading presentation on the HUD. The other six maintained an approximately optimum speed and adjusted the climb using the altitude information presented in the HUD. They considered that the speed resolution of the energy-maneuvrability display was too coarse to allow smooth pitch attitude control.

Climbs performed with the HMMD information available were completed in an average of 68 s, compared with 71.3 s for unassisted runs. Although this 3 s difference is insignificant relative to the grosser variations between subjects and repetitions, it is more likely to be due to the higher average speed at the completion of the previous turn than a more rapid gain in height.

4.1.3 The 180° turn

Since this manoeuvre was followed by a dive, it was reasonable to turn in the most rapid fashion without conserving energy. Only one pilot used the HMMD image, when available, to achieve the airspeed and load factor which produced the greatest attainable turn rate. Most of the subjects suggested that the display was useful initially to avoid exceeding the structural load limit, but that once the turn was set up the maximum turn rate could be attained by holding the aircraft at the maximum angle of attack, which was displayed in the HUD. The objective measures reinforced the absence of any significant effect due to the availability of the energy-maneuvrability data.

4.1.4 The dive

Most pilots rolled the aircraft to an inverted position, pitched down until descending at about 60°, rolled upright, continued the descent to about 5000 ft, and then pulled-up to finish straight and level at about 1000 ft. The throttle was set to 'idle' and the airbrake operated to prevent an excessive accumulation of speed in the dive. None of the pilots considered the energy-maneuvrability data to be useful during the manoeuvre, except one who thought it helped to avoid exceeding the structural limit during the pull-up at low level. Again, there was no significant performance difference.

4.1.5 The loop

A few subjects used the energy-maneuvrability display to avoid overstressing the aircraft during the initial pull-up into the loop, but as height increased and speed decreased it was only necessary to hold the aircraft at the maximum angle of attack. Consequently, it was considered easier to maintain attention on the HUD parameters throughout the rest of the manoeuvre. There was a small, but statistically insignificant, increment in the average time taken to complete loops when the HMMD image was available.

The overall performance measures are summarised in Fig 10 as a diagram showing the cumulative number of manoeuvres completed within a given elapsed time for runs completed with, and without, the aid of the energy-maneuvrability information. This figure shows that the inconsistent effect of the extra data is small in comparison to the variation between pilots, and with repetitions.

In general, the errors which arose during the exercise were not affected by the presence of the HMMD image. Overstressing the aircraft occurred most frequently, (18 instances), particularly during the pull-up from the dive, but there were also some scheduling errors, such as continuing a turn beyond the required heading (3 instances). The other differences in performance produced by the subjects were due to their differing techniques and responses to the manoeuvre instructions. For instance, one subject flew the first turn at a higher speed than optimum but, in this case, the time forfeited was re-couped by requiring a shorter acceleration before climbing. Other subjects preferred to 'bun.' when levelling at altitude or initiating the dive, rather than roll to an inverted attitude and apply a positive load factor.

Overall, it was suggested that by remembering a few crucial performance parameters for each manoeuvre the energy-maneuvrability information could be neglected throughout the whole sequence. The few pilots who did make active use of the extra information did so at the expense of considerable extra attentional effort, except when using it as a relatively convenient 'g'-meter. However, as with the previous simulation, this broad conclusion may have arisen from the paucity of natural cues in the simulator which, when combined with the exactness and predictability of the required manoeuvre, made it advantageous to rely on information presented by the HUD.

5 THE THIRD SIMULATION: CC 'BAT MANOEUVRING

This, the final planned exercise, is currently underway. The objective is to assess the pilot's ability to make use of the HMMD and the energy-maneuvrability format to obtain optimum aircraft performance whilst keeping a target in view during combat manoeuvring.

Three display conditions are used. The first is the (datum) case of a cockpit containing conventional instruments and a HUD. The second retains these displays but the pilot also has the HMMD presenting the energy-maneuvrability format, whilst in the third condition the HMMD provides an alternative format containing separate airspeed and load factor indicators, as shown in Fig 11. A

counteract this using an unnaturally high head posture. The image was of acceptable quality and the information could be assimilated easily.

The most relevant and virtually unanimous opinion was that the availability of the HMMD information made little difference to the manner in which the pilots performed the task. Five of the six relied solely on the HUD, finding this information more easy to use and more comprehensive. It was considered to be more convenient to include all the HUD information, the timing, and engine rpm data in a scan, and ignore the HMMD. The idea of using the HMMD image as a quick indication of the aircraft state was not attractive, because the digital presentation made it difficult to assess the rate at which the aircraft was departing from the required flight parameters.

These subjective conclusions were reinforced by the objective performance measurements shown in Fig 8, which gives the joint performance of each subject for the 'flying' and 'detection' tasks, on graphical axes arranged so that improved searching moves a point upwards and an increase in flying accuracy moves a point to the right. Target detection performance was assessed from the number of targets detected, and the flying accuracy was the average deviation of height, speed and heading from the required values expressed as a percentage of the allowable errors. This method of describing the combined task performance indicates that the largest variation in performance arose from differences between subjects, largely because they applied different priorities to the two component tasks. The effect of the availability of the HMMD information was to introduce small improvements to the combined task performance for some subjects, an apparent change in the trade-off between the two tasks for others and a small decrement for the rest. Comparing the mean level of combined performance over all subjects for the two conditions shows negligible change due to the availability of the HMMD image.

This result may, however, be due to the paucity of visual cues, and the absence of kinaesthetic cues to assist in controlling the simulated aircraft, which combined with the comparatively exacting flying performance, produced an exercise with an unlikely mixture of precise 'instrument flying' and a visual external search.

4 THE SECOND SIMULATION: THE MANOEUVRE SEQUENCE

This exercise was arranged so that subjects could become familiar with the energy-maneuvrability format and so that the implementation of the format could be checked prior to the main exercise. It also provided an opportunity to assess whether the comparatively novel form of presentation could be assimilated, and whether it enabled a pilot to extract improved performance from an aircraft (Ref 8). The pilot's task consisted of flying a sequence of five manoeuvres which demanded that the aircraft be flown to its appropriate limit. The usefulness of the energy-maneuvrability information could then be assessed from any decrease in the time taken to complete the manoeuvre sequence.

The simulator behaved as a modern lightweight fighter in which the main flight information was presented on the head-up display and an additional cockpit-mounted 'g' meter. There was no interaction with a target aircraft and the main external visual cue was the horizon, separating the blue sky and brown ground, projected onto the inner dome surface.

The sequence began at low level and slow speed, the first manoeuvre being a horizontal turn through 360° which lead into (No.2) a climb to 20000 ft. Having attained this height the pilot performed, (No.3) a horizontal turn through 180° , (No.4) a dive down to 1000 ft and finally, (No.5) a loop, ending straight and level. The eight pilots were allowed adequate time to become familiar with flying the simulated aircraft at its limits and the behaviour of the energy-maneuvrability display. They also practised the manoeuvre sequence, both with and without the use of the HMMD information. The first two subjects were asked to fly to an accuracy of ± 250 ft in height and ± 5 deg in heading, but these demands were relaxed to ± 1000 ft and ± 10 deg for the remaining six subjects so that they could allocate more attention to the control of speed and load factor, rather than be preoccupied by the accuracy of the flight path. Each pilot completed the sequence six times and during three of the runs the HMMD was active, alternating with three others in which only the HUD and the 'g'-meter were available. The sequence was reversed for half the subjects to avoid ordering effects. Operation of the simulator was monitored using a monochromatic split-screen video presentation in which the HUD information, the HMMD format and an overhead view of the pilot were combined, as shown in Fig 9. The signal was recorded as a means of carrying out subsequent assessments.

4.1 Results and conclusions

The energy-maneuvrability format was visible, readable and understood by all the subjects, although some blurring and miss-focussing was apparent. It was also considered to be relatively easy to switch attention between the HUD image and the HMMD image, all pilots preferring to position the HMMD image very close to the HUD field. Only one subject reported any difficulty interpreting the significance of the individual points, and that was due to head tilts, which rotated the image. Two subjects became temporarily unsure of the significance of a point when it was overlaid by the aircraft state symbol. Most subjects reported considerable confusion when the airspeed or load factor temporarily exceeded the available range causing the state symbol to disappear off-scale. They favoured limiting the allowable excursion so that the symbol remained within the field of view, but reducing the number of elements making up the symbol to indicate that the appropriate parameter was beyond the scale limits. All of the subjects thought that the presentation of a complete line diagram, rather than the five optimum points, would be unnecessarily cluttered.

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5 THE THIRD SIMULATION: COMBAT MANOEUVRING

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comparison of the objective outcomes and the subjective opinions for these three conditions will show whether the HMMD provides a conveniently placed image, and whether the graphical energy-maneuvrability format is more useful than the component parameters.

A total of three pilots will use each of the display conditions to perform three tasks. In the first, the simulated aircraft and the target start on opposite sides of a horizontal circle, arranged so that the target maintains the maximum rate of turn, and the pilot attempts to gain a position as close as possible to the target's tail. In the second task the object is to turn and chase an overflying evasive target, whilst in the third the target behaves in an aggressive evasive manner and the pilot must manoeuvre to a position from which a missile can be launched.

6 FUTURE STUDIES

The present range of simulation exercises is intended to assess the likely usefulness of specific parameters presented on the HMMD in a limited range of operational circumstances. Further studies are necessary in which the HMMD is integrated into the cockpit as part of the total information management system, performing a role which is complementary to the present range of displays. This will require a helmet position-sensing system and the provision of a number of alternative formats suitable for the current phase of the mission. Only then will the matrix display, coupled with a helmet-mounted sight, be assessed as a mission-long aid for target designation, radar cueing, missile launching, obtaining the best aircraft performance, and for warning the pilot about system failures, the possibility of being attacked, or of colliding with the ground.

7 CONCLUSIONS

The helmet-mounted matrix display has been assessed in a flight trial, and in an incomplete series of simulation exercises. Results from the flight trial suggest that the device can provide an adequately clear and visible image provided the image brightness is increased and more positional and optical adjustments are incorporated.

The bulk, weight, forward extension of the centre of mass, and visual restrictions which result from the device, were only considered acceptable in the conditions provided by the trial, but not for operational use. Further development must improve these facets.

The first simulation study concluded that the device was not useful when arranged to present general flight information during a Combat Air Patrol Mission, and the second suggested that a novel form of energy-maneuvrability format did not assist pilots to obtain better performance from the simulated aircraft. However, both of these conclusions could have been due to the lack of visual and kinaesthetic cues provided by the simulator and the unusually exacting nature of the flying task.

The usefulness of the device, as a means of presenting the energy-maneuvrability format during combat manoeuvring against a target aircraft, is the subject of a current simulation study.

Acknowledgments

The enthusiastic participation of the Cranfield Institute of Technology, the Flight Automation Research Laboratories of Marconi Avionics and, particularly, the subjects, has been much appreciated.

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Fig 1 The matrix display on the RAF Mk 4 helmet

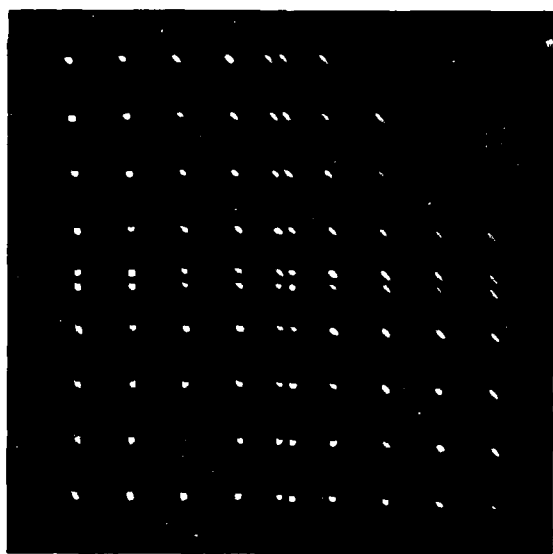


Fig 2 Photograph of the image projected by the HMMD. (Camera fitted with external 3 mm diameter aperture, positioned on optic axis)

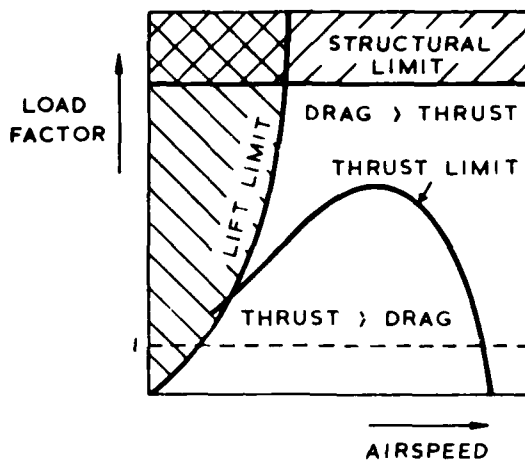


Fig 3 The basis of the energy-maneuvrability format

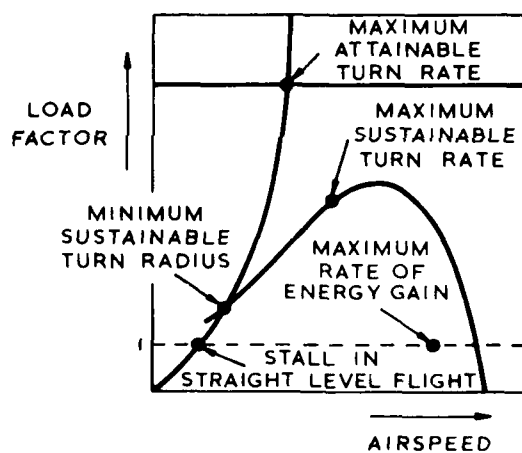


Fig 4 Points of special significance on the energy-maneuvrability format

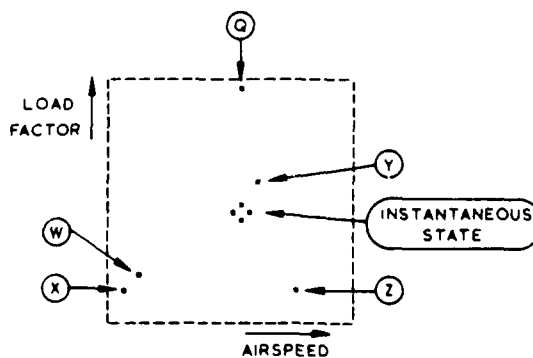
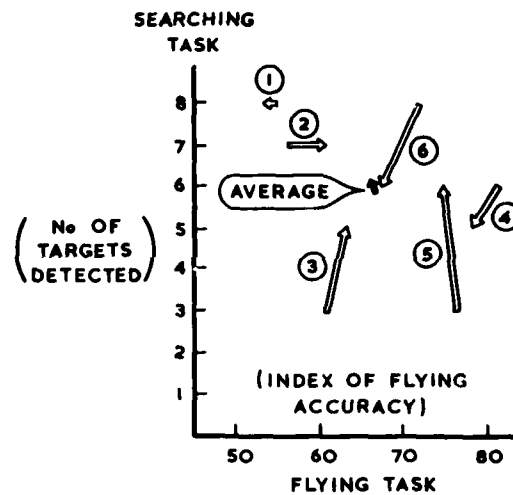


Fig 5 The energy-maneuvrability format presented on the HMMD



Fig 6 The Morane-Saulnier 'Paris' aircraft



ARROWS SHOW THE CHANGE IN PERFORMANCE PRODUCED BY THE HELMET-MOUNTED MATRIX DISPLAY FOR EACH OF THE SIX SUBJECTS, AND THE AVERAGE, DURING THE SIMULATED C.A.P. EXERCISE.

Fig 8 Flying accuracy and searching performance for each subject carrying out the simulated CAP task



Fig 7 Subject wearing the HMD with correct placement of the optics relative to the subject's eye



Fig 9 Example of a split-screen video frame from the manoeuvre sequence exercise

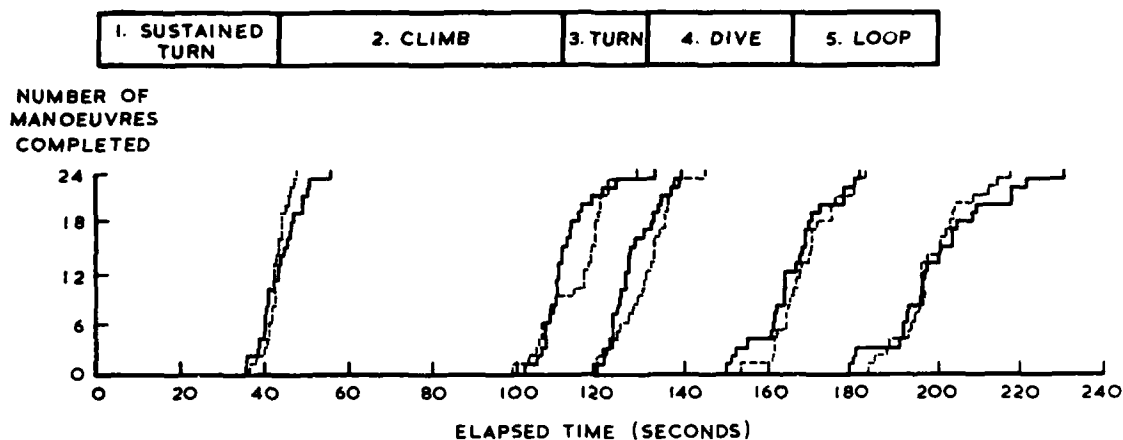


Fig 10 The overall results of the manoeuvre sequence exercise. Solid lines represent the runs completed with the aid of the HMMD

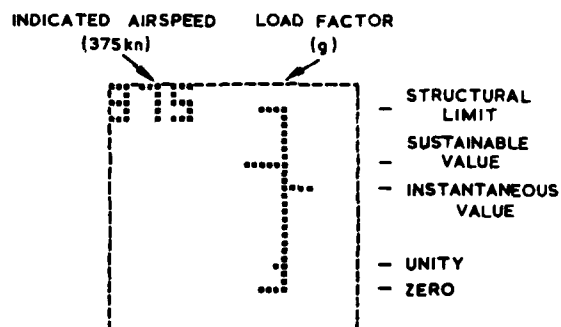


Fig 11 The alternative format for use in the third simulation exercise. Airspeed and load factor are displayed as separate parameters, but the latter scale presents the instantaneous value, the zero and maximum values, and the value which can be maintained at the current airspeed

EVALUATION OF A PILOT WORKLOAD ASSESSMENT DEVICE TO TEST ALTERNATE DISPLAY FORMATS AND CONTROL HANDLING QUALITIES

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SUMMARY

This in-flight research project evaluated the utility of a Workload Assessment Device (WAD) to measure pilot workload for approach and landing tasks under simulated instrument meteorological conditions, alternate HUD formats and control stability variations. The flight tests were conducted in an NT-33A research aircraft, extensively modified for the U. S. Air Force and U. S. Navy by the Display Evaluation Flight Test program. The hardware, software, and test procedures associated with the WAD functioned efficiently with only minor discrepancies and minimum pilot distraction. The project established the feasibility of using an item-recognition task as a measure of sensory-response loading and reserve information processing capacity while flying precision approaches. In a descriptive statistical treatment of the data, the results indicate an appreciable increase in reaction time and errors with degraded handling qualities as compared to ground baseline measures and good handling qualities. The preliminary findings also reveal consistent trends toward the availability of more mental reserve capacity when flying predominantly pictorial/symbolic HUD configurations as compared to conventional HUD formats with scales and alphanumerics. It is recommended that further evaluations be conducted to establish the efficacy of utilizing the WAD to measure mental workload in a wide variety of aircrew tasks.

INTRODUCTION

BACKGROUND

New developments in cockpit display designs and integrated weapons system avionics have significantly altered the role of the pilot from that of a skilled, manual control operator to an executive manager of an integrated weapons system. Emphasis on psychomotor control has been augmented by an interest in more cognitive skills represented by such functions as short-term memory, information processing, and decision making. Few measurement techniques exist which are able to provide an objective, reliable, and valid estimate of the subtle differences in workload introduced by these new systems. To date, methodology for objectively quantifying workload has not been effectively applied to the flight test and evaluation of aircrew systems (references 1 and 2).

This project introduced a novel approach to the traditional manner of measuring pilot workload. Aircrew workloads are typically measured by subjective assessment rating scales which are based on pilot opinions that relate operational task demands to system response characteristics, e.g., Cooper-Harper Handling Qualities Rating Scale. The new approach applied in this project is an item-recognition task first identified by Sternberg (reference 3) and modified by the U. S. Air Force (reference 4) to measure the reserve capacity of the pilot. The approach assumes that an upper bound exists on the ability of the pilot to gather and process information. As the pilot's workload increases on the primary task, i.e., flying the aircraft, reserve capacity for processing secondary information decreases until a point of overload is reached by the pilot. At this point, the information processing demands of the task exceed the pilot's total workload capacity and is manifested by degradation in performance (i.e., increase in errors and response times) on the secondary item-recognition task.

The theoretical formulation of the item-recognition task, as proposed by Sternberg (figure 1), has several attractive features which make it ideally suited for evaluating the source of increase in task-loading in aircraft test environments. The theory assumes a least-squares, linear regression fit of the data where the intercept represents the input/output component and the slope depicts the mental information processing component of the item-recognition task. If, for example, the sensory-response mode (i.e., input/output), is response overloaded the theoretical expectation is a change in the y-intercept of the regression line with no change in slope. Conversely, if the source of task-loading was one which affected the pilot's mental information processing capabilities (e.g., short-term memory overload), the expectation is a change in the slope of the curve without a corresponding change in the intercept value. Either result would be a decrease in the pilot's reserve capacity for processing information.

The use of the item-recognition task to assess primary task workload is not a new concept in aircrew flight simulation studies (references 5 and 6). However, the uniqueness of its application in this project is that a Workload Assessment Device (WAD) that generates and controls the secondary item-recognition task was designed, fabricated, and installed in a NT-33A research aircraft to measure and analyze the pilot's reserve workload capacity for the Display Evaluation Flight Test (DEFT) program as reported in reference 7.

PURPOSE

The purpose of this project was to evaluate the utility of the WAD to measure pilot workload for approach and landing tasks under simulated Instrument Meteorological Conditions (IMC's) for alternate HUD formats and aircraft control stability variations.

DESCRIPTION OF AIRCRAFT/EQUIPMENT

The NT-33A variable stability aircraft is an extensively-modified, T-33 jet trainer. The elevator, aileron, and rudder controls in the front cockpit were disconnected from their respective control surfaces and connected to separate servo-mechanisms that comprise an "artificial feel" system. In addition, the elevator, aileron, and rudder control surfaces were connected to individual servos which were driven by a number of different electrical inputs. This arrangement, through a response-feedback system, allowed the normal T-33 stability derivatives to be augmented to the extent that the handling qualities of the hypothetical research configurations could be simulated. A more comprehensive description of the NT-33A can be found in reference 8.

The DEFT program also provided a fully software-programmable display system to complement the variable stability features of the host-modified NT-33 Aircraft. Relative to the aircraft configuration, the DEFT system provided the capability of changing display formats and changing the algorithms and dynamics of the display driving signals. The display system consisted of a HUD, two digital computers, a magnetic tape system, INS sensors to augment the existing aircraft sensors, and a display repeater and mode control unit for the aft cockpit.

The software programs provided an in-flight choice of two uniquely different display configurations for use in the approach and landing phases of flight. These displays were of a conventional HUD format (figure 2) and the predominantly symbolic Klopstein format (figure 3). As depicted in the figures, the conventional display used a HUD format with a flight path ladder, scales, and alphanumeric readouts of various flight parameters. The Klopstein display, however, is predominantly symbolic/pictorial depicting the horizon, and artificial runway overlaying the actual runway, and other flight guidance symbols.

METHOD

After several practice sessions and prior to the start of the evaluation flights, a baseline measurement was obtained on the item-recognition task. Each pilot was given the item-recognition task for each memory set size while sitting in the cockpit of the aircraft stationed on the ground. The task required the pilot to memorize sets of one, two, or four letters, i.e., A, RJ, ZPNW. The pilot was then instructed, prior to testing with each memory set, which set of letters would be presented for memory recall. The prememorized letters (positive) or other letters (negative) were presented on the HUD one at a time every 7 sec. The positive and negative letters were presented individually with a .5-probability of occurrence. Each letter appeared on the HUD one at a time until the pilot responded or 5 secs. elapsed. The pilot responded to a letter presentation by pressing one of two designated buttons on the control stick. One button indicated that the letter was a member of the prememorized set (positive) and the other indicating it was not a member of the prememorized set (negative). Positive letters never appeared as negative letters and the same positive letter sets were used throughout the test. A total of 30 letters, 15 positive and 15 negative, was presented for each memory set for the baseline conditions.

The same procedures were used in flight as during the baseline test conditions with the exception that the pilot was flying the aircraft while performing the secondary task. An additional experimental control allowed one approach per handling quality/display format combination to be flown without any letter presentations to evaluate the impact of the secondary task on the primary task of flying the aircraft.

The reaction times and response errors were collected and analyzed by the WAD controller and ground-based analysis system. After each response, the reaction time was measured from the onset of a letter to the physical response of pressing the correct button. The reaction times for both the positive and negative letters were stored on cassette tapes. The reaction times for the correct responses were then averaged and plotted as a function of the memory set sizes. The response errors were coded, tabulated, and categorized by type of error and frequency of occurrence. A response was considered an error if the pilot pressed the wrong key (reversal error), responded correctly but after 1,500 msec (out-of-bound error), or did not respond before 5 sec (time-out error).

The basic flight scenario for each approach and touch-and-go was as follows. The Evaluation Pilot (EP) was given control of the aircraft by the Safety Pilot (SP) with the desired display-aircraft handling quality combination. The EP then flew on instruments while using an orange filter over the windscreen and a blue visor attached to the helmet

to simulate IMC.¹ After intercepting the glide slope, the EP descended to 1,800 meter MSL to intercept the localizer at 8 nmi. At this point, the SP turned on the digital recorder and the WAD controller which were used to record the primary flight measures and the secondary task measures, respectively. The EP proceeded to fly the glide slope and the localizer to perform the approach. The outer marker was at approximately 4 nmiles. At 200 meter AGL and approximately 1/2 nmi from the runway threshold, the EP "broke out" (i.e., he lifted the blue visor) and flew visually for the remainder of the low approach (7 meters AGL). If conditions permitted (fuel state, crosswind, etc.), the EP then performed the touch-and-go landing, minimizing the sink rate on touchdown to less than 1 meter/sec. The touchdown point was a 170-meter zone, 500 meters from runway threshold. After liftoff and at approximately 70-meter AGL, the SP turned off the WAD controller and the digital recorder. After four approaches, the SP assumed control of the aircraft, then changed the pitch handling quality to the next desired setting and again released control of the aircraft to the EP.

After each block of four approaches was completed under the same pitch handling quality, the EP and SP rated the approach and flare/landing segments of the flight profile using the Cooper-Harper pilot rating scale. Additional commentary data were gathered from the EP and SP throughout the flight tests by use of an audio tape recorder, e.g., comments on degree of air turbulence.

The WAD consists of two basic units: the airborne controller and the ground-based analysis center. The controller is configured for installation in the front avionics bay of the NT-33A research aircraft. The unit provides the electronics, power supply, software, interfaces to the HUD and the aircraft intercom, rear cockpit initialization switches, control stick response switches, and data recording system necessary to perform a complete series of item-recognition experiments. In addition, the controller can operate as a stand alone laboratory system capable of performing the same tasks as when airborne. The ground-based data analysis center is used to initialize several software options of the controller and to reduce and analyze response time data. A description of the functional capabilities of the hardware and software is discussed in appendix A. A detailed description of the complete WAD system is contained in reference 9.

SCOPE

Each pilot flew two evaluation flights using the conventional HUD format and two with the Klopstein format. During each evaluation flight, a pilot performed eight approaches terminating in either a low approach or touch-and-go landing for a total of 32 approaches per pilot. One-half of the approaches for each flight were made using "good" handling qualities, the other half were made using either "fair" or "poor" handling qualities. The handling qualities were manipulated by changing the pitch response (150 msec or 200 msec time delay) of the aircraft after every four approaches. The response of the roll and yaw axes was held constant throughout the tests.

RESULTS AND DISCUSSION

GENERAL

The test and evaluation paradigm used in this project was a repeated measures design in which type of display format (conventional versus Klopstein), flight handling quality (good versus poor), and secondary task difficulty (memory set sizes, 0, 1, 2, and 4) were fractionally combined to form 16 different conditions. It was planned that the two EP's would be exposed to each of the 16 conditions twice. However, each EP was able to complete all combinations of the test conditions only once. Out of a total of eight 1.5-hr evaluation flights, a complete set of secondary task data was analyzed for four flights only.

The results showed that the general procedures established for the conduct of the evaluation flight tests of the WAD were acceptable to the pilots. The in-flight test procedures provided the EP's and SP's with reliable guidelines for efficient and safe crew coordination during successful approaches and during incidents of all equipment malfunctions. Pilot comments aided in the investigation of the most salient characteristics of the item-recognition task including the selection, location, and timing of the letters as presented on the HUD. A thorough testing of the WAD procedures during the project resulted in only minor software changes and hardware replacements and clearly established the feasibility of using the item-recognition task for in-flight tests.

PRIMARY FLIGHT MEASURES

The primary flight measurement data taken from the digital recorder were divided into two defined categories of approach and flare/landing. Because of the length and complexity of the analyses of the primary flight measurement data, the results were published under separate cover in reference 10.

The summary results of these analyses indicate that the primary flight performance parameters and Cooper-Harper ratings showed a general inconsistency between displays and handling qualities during the approach and flare/landing phases of the flight task.

¹ Overlaying the two complementing colors produced a perceptual environment similar to night IMC when the pilot attempted to view the external world.

Lack of systematic differences in the primary flight measures and Cooper-Harper ratings suggests that pilot performance remained the same for all conditions. That is, no significant differences were found in the primary flight measures between display formats, handling qualities, or memory set sizes. These findings indicate that the pilots compensated for the increased task difficulty by maintaining primary flight performance at an acceptable level. However, this pilot compensation was not without cost. A loss of information processing reserve capacity can be clearly shown from the results of the secondary task measures.

SECONDARY TASK MEASURES

Secondary task measures consisted of reaction times in which slopes and intercepts were calculated after solving linear regression equations for each set of data. Secondary task errors for the item recognition task were calculated for all incorrect responses, late responses, and no responses.

REGRESSION EQUATIONS (REACTION TIMES)

The reaction times associated with each correct response were averaged for the complete flight profile for each m-set size (letters 1, 2, or 4), handling quality (good or poor), and display format (conventional or Klopstein). Linear regression equations were then calculated to indicate the slope and intercept of the plotted data as shown in figures 4 and 5. The data reveal that both the intercept and slope of the curves for each pilot increased from baseline conditions when the handling qualities were degraded. The results indicate that the WAD is sensitive to the increased sensory/response and mental processing requirements imposed by the addition of a secondary task and to the level of difficulty of that task. For example, the largest intercept and slope changes occurred between each subject's relative baseline and poor handling quality condition.

A closer examination of the data reveals that the differences in the magnitude of change in the slopes were consistently larger for the conventional HUD format than the pictorial Klopstein HUD format under either good or poor handling qualities. This trend, relative to each subject's shift in slope magnitude, suggests that more mental reserve capacity was available to process information while flying the Klopstein display than the conventional HUD format and while good handling qualities independent of the type of display format used.

Reviewing the resulting changes in intercepts revealed a similar trend with regard to the handling quality parameter. The average increase in the magnitude of change in intercept was less for conditions of good handling qualities than for poor handling qualities. However, with regard to the display variable, the trend was reversed from that observed for the changes in slope; i.e., the average intercept value changed less for the conventional format than for the Klopstein. Assuming the observed trends would persist in a larger data sample, the results indicated that degrading the handling qualities had a consistent effect on the input/output stages of the item-recognition task, whereas the effect of the display format variable on the input/output stages of the task was subject to inconsistent individual differences. The lack of consistent trends in the changes in intercept relative to the display variable may be due to: (1) individual differences in establishing a time-error tradeoff,² (2) locations of the letter in relationship to differences in eye scan patterns, and/or (3) different strategies of memory recall.

These results suggest that degrading handling qualities had a consistent and predominant effect of reducing the pilot's reserve capacity for all three stages of the information-processing, secondary task. Changing the display formats appeared to yield similar results but are subject to the influences of individual differences with regard to the mental component of the information processing task.

The reader is reminded that these data reveal only trends and were gathered from a sample of two pilots. Additional flight data are required with a larger pilot sample and more replications of test conditions before definitive conclusions can be made concerning the reliability of the results of these measures. A further discussion of the reliability of the item-recognition task that questions the day-by-day stability of the slope and intercept is found in reference 11.

PERCENT ERRORS

The WAD provided an accumulative record of the number of errors, sequence of occurrence, type of error, and reaction time associated with each error for both positive and negative letters. The combined percent of secondary task errors for both pilots is shown in figure 6. The error data show that as the difficulty of the secondary task was increased, i.e., as the m-set size increased, a corresponding decrease in response accuracy was observed which supports the expectation of increased error rate under conditions of task overloading.

The increases found in secondary task response errors under conditions of poor handling qualities for both display formats are consistent with the results of the slope and intercept reaction time data with regard to the influence of degraded handling qualities.

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The increases found in secondary task response errors under conditions of poor handling qualities for both display formats are consistent with the results of the slope and intercept reaction time data with regard to the influence of degraded handling qualities.

² The EP's were only instructed to respond as quickly and accurately as possible to the secondary task while flying a precision approach and landing.

That is, under test conditions producing a reduction in reserve capacity, a corresponding increase in response errors occurred.

In contrast, the reaction time data indicated that the type of display format differentially influenced both the input/output and mental stages of the information processing tasks, whereas response error data showed a consistently higher degree of response accuracy under conditions of the pictorial Klopstein display format.

To further explore these results, the total percent errors were classified into type of error for each handling quality and display format. The secondary task errors reveal that the total percent errors were evenly distributed between incorrect responses (reversals), late responses (out-of-bounds), and no responses (time-outs). However when the total percent errors are differentiated between display type and handling quality, it clearly shows that three times as many reversal errors were committed by the EP's flying the conventional HUD than the Klopstein display format. Degrading the handling qualities increased the percentage of time-out errors for the EP's flying with the conventional display and increased the out-of-bounds under the Klopstein display format. Since it was assumed that a time-out error would reflect a greater decrement in reserve capacity than an out-of-bounds error, these results would imply that the EP's had less reserve capacity while flying under the conventional HUD and degraded handling qualities than the Klopstein display format.

In summary, the percent of secondary task errors increased whenever the memory set size increased, the handling qualities were degraded, and the task was performed in flight under the conventional display format conditions. Poor handling qualities primarily induced errors of delay or no response while the type of display affected mainly the accuracy (correctness) of response.

CONCLUSIONS

The hardware, software, and test procedures associated with the Workload Assessment Device (WAD) functioned efficiently with only minor discrepancies and minimum pilot distraction.

The project established the feasibility and sensitivity of using a secondary item-recognition task as a measure of sensory/response loading and reserve information processing capacity while flying precision instrument meteorological conditions approaches.

The pilots showed an appreciable increase in reaction time and percentage of errors on the secondary task flown under poor handling qualities as compared to good handling qualities and ground baseline conditions.

The WAD revealed that the pilots had less secondary task errors, more mental reserve capacity, but longer reaction times attributed to sensory/response delays while flying with pictorial/symbolic HUD configurations (Klopstein) than conventional HUD formats.

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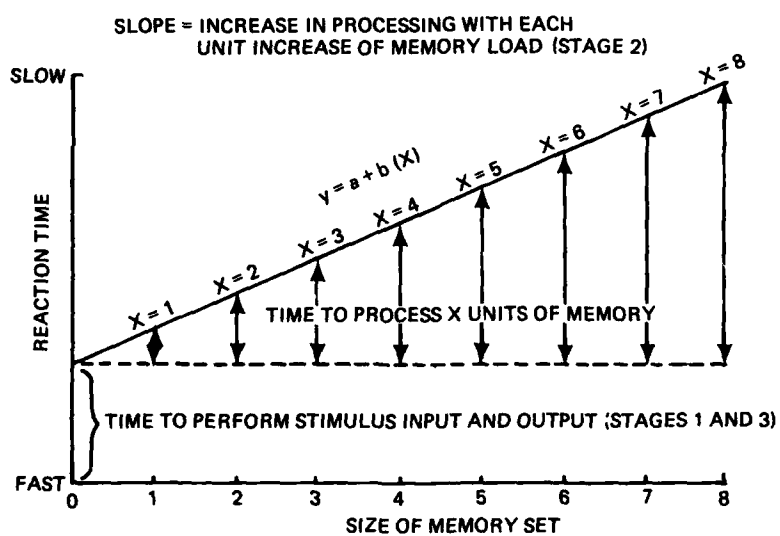


Figure 1 Theoretical Components of the Item
Recognition Task Proposed by Sternberg

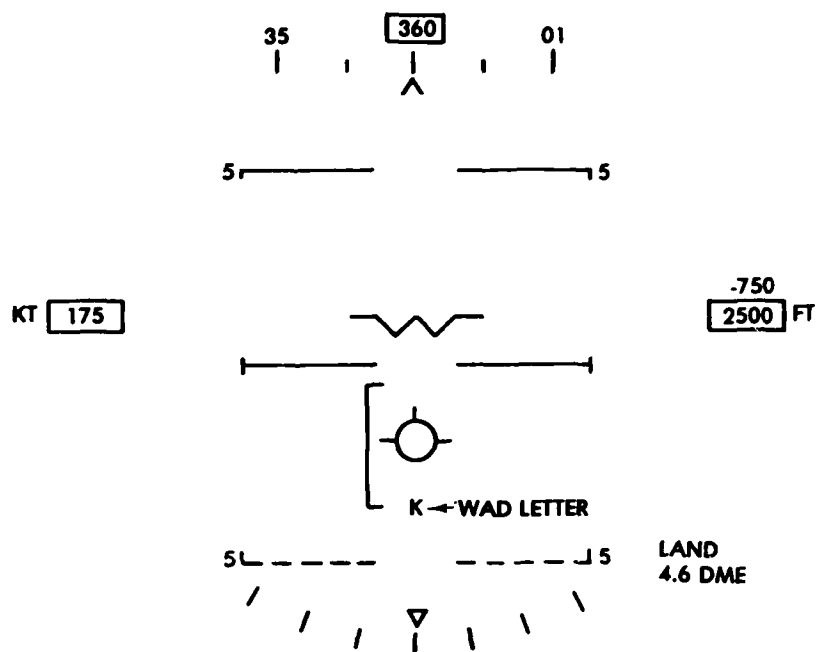


Figure 2 Conventional HUD Format

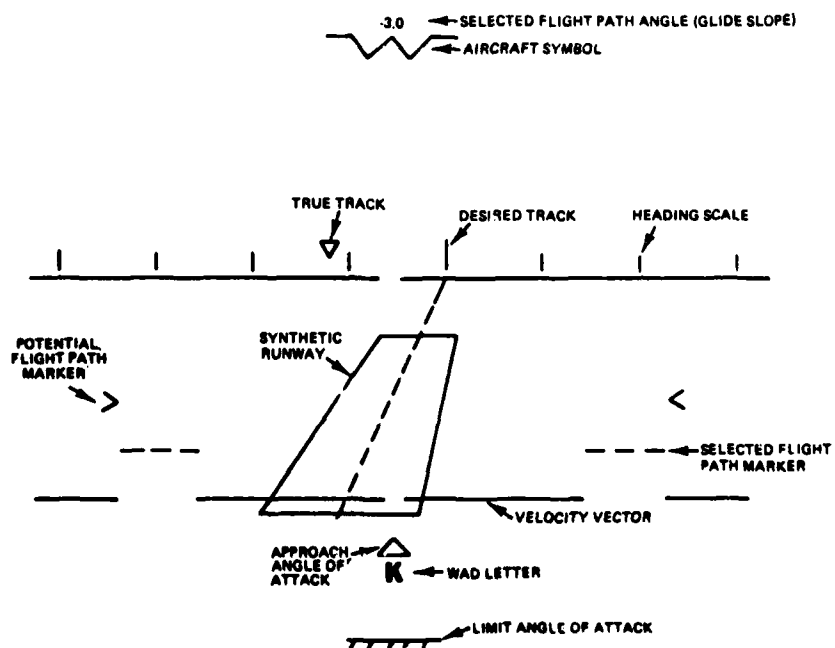


Figure 3 Klopstein HUD Format

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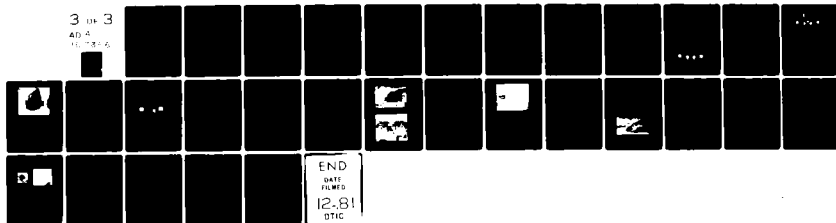
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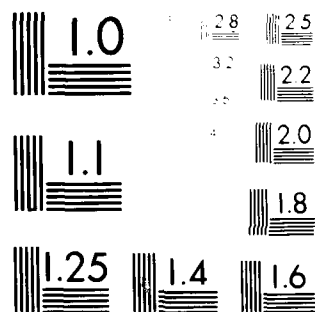
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MICROCOPY RESOLUTION TEST CHART
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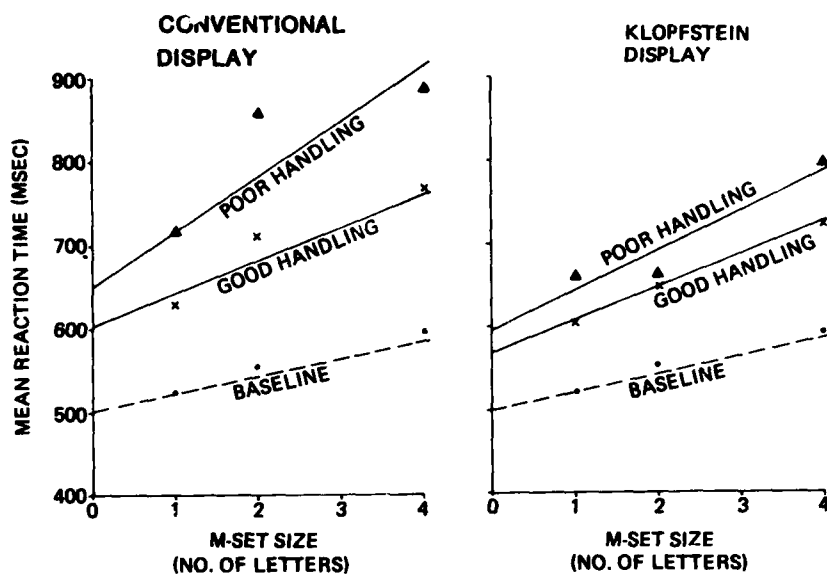


Figure 4 Linear Regression Lines for Evaluation Pilot 1

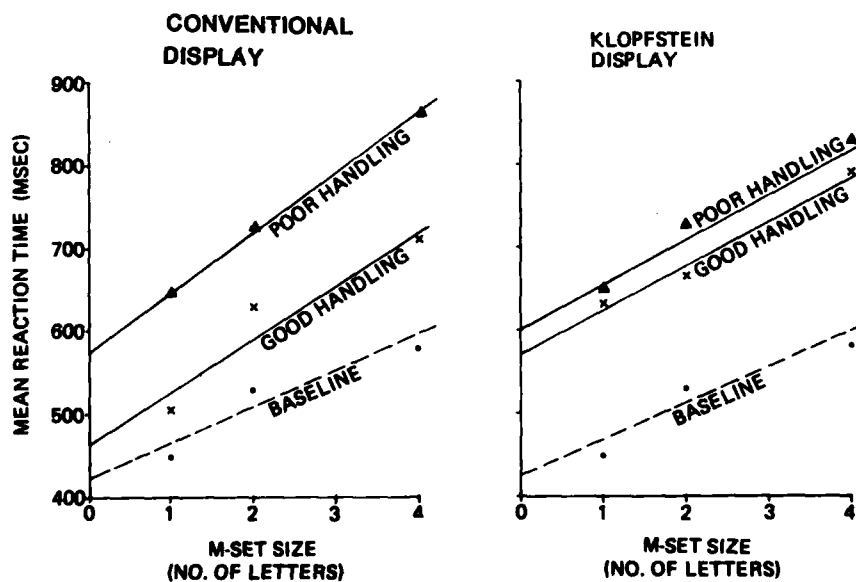


Figure 5 Linear Regression Lines for Evaluation Pilot 2

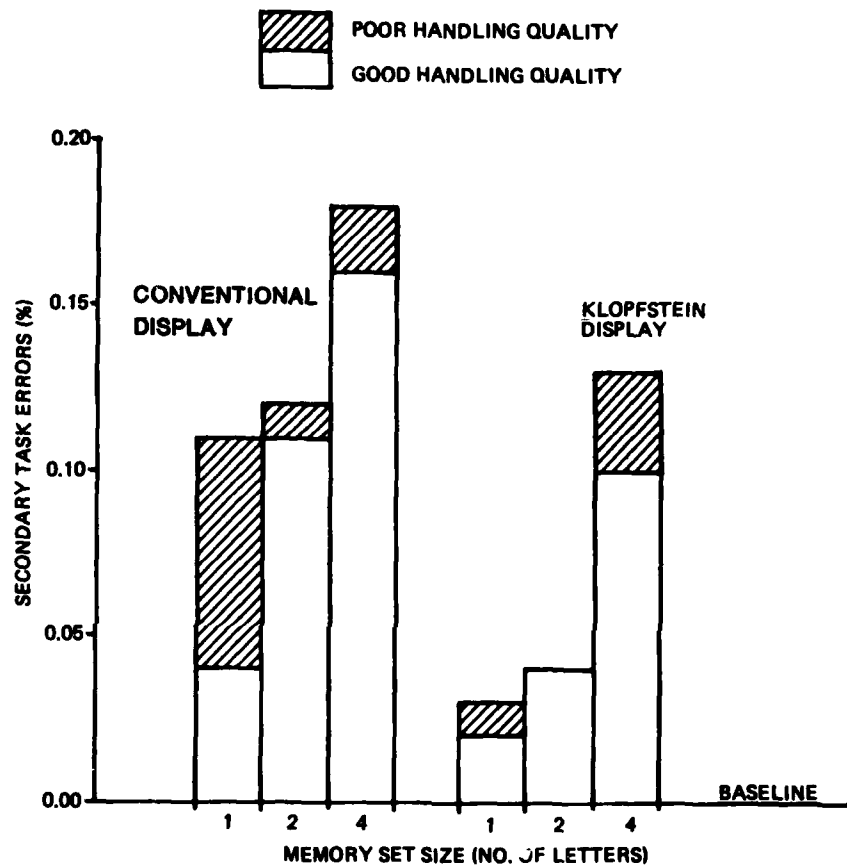


Figure 6 Mean Percent Secondary Task Error for Memory Set Size (Number of Letters) by Display Format and Handling Quality

WORKLOAD ASSESSMENT DEVICE SYSTEM DESCRIPTION

TASK

The Workload Assessment Device (WAD) presents to the subject an item recognition task that requires him/her to respond to aural or visual stimuli that are composed of alphabetic characters or symbols. After a stimulus has been presented, the subject responds by pressing one of two switches to indicate the stimulus is (1) part of a pre-memorized set of letters, or (2) is not part of the set (1). The data collected are the reaction times, in milliseconds, from the onset of a stimulus presentation to the physical response of pressing a button.

When a trial is completed, the subject is given another set of letters to memorize and the sequence is then repeated. Usually four trials are included in a given session with the memory size ranging from one to four letters. Data analysis consists of determining mean reaction time to a number of presentations, and the standard deviation of the response reaction times.

SYSTEM CONFIGURATION

Given the above task, its complexity, number of possible deviations, and timing considerations, a microprocessor was chosen for the main controller. Peripheral devices are manipulated using software located in programmable memory, (RAM). All data collected are temporarily stored in memory and subsequently recorded on a digital cassette tape. When the mission is completed, the tape is retrieved from the real-time controller and taken to a ground-based data analysis computer. Prior to each mission, certain parameters are entered into the ground-based computer and written, along with the operating software, to the cassette tape. These parameters are used by the main controller in order to present variations of the task described.

The system configuration is shown in Figure A-1 and consists of a real-time controller and data collection device, software, and a ground-based data analysis package.

In order to provide for portability, a chassis was constructed to fit into a specific location in the nose of the NT-33A aircraft. The chassis is small enough to fit into a standard off-the-shelf enclosure and light enough to be hand portable. The control panel of the WAD has three connectors that provide all interface signals required for operation. In the portable mode, these connectors provide I/O lines that can be interfaced to various display devices and response keys such as used in many simulators and laboratory environments.

HARDWARE

The Workload Assessment Device (WAD) was designed around the IEEE 696.1/02 buss, (S-100). This buss configuration was chosen for the size of the printed circuit board, availability, and cost. Most S-100 devices manufactured today are reliable and well constructed, and there exists a large base of different peripherals to choose from. Since this system is experimental and cost a major concern, it was not required to meet government/mil specifications for reliability, temperature, and vibration.

The WAD mainframe contains 5 slots that are used for the various peripheral interfaces, memory, and CPU. A single board computer manufactured by Cromemco, Inc., is used for the main controller. It contains a serial I/O port, several parallel I/O lines, real time clock, Read Only Memory (ROM), Programmable Memory (RAM), and all necessary system timing signals. A 16K RAM board is used for program and data storage. The next buss location contains the digital cassette interface which is connected to the NFE Corporation digital tape recorder located on the front panel of the WAD. The fourth slot contains a 16 channel analog to digital (A/D) converter and interface. This unit is connected through cables to the aircraft's analog computer and can be used to monitor up to 6 different control surfaces that will be used in a derivation of the described item recognition task. The fifth position contains the speech synthesizer board. This board contains the new National Semiconductor speech processor IC along with its ROM vocabulary ICs.

SYSTEM OPERATION

When power is applied to the system, a boot program located in ROM loads a file from the cassette tape recorder. This file contains a program that controls all operations of the item recognition task. After loading, the program gains control of the system and waits for a command from the serial port. The experimenter has several options at this time. Usually, he will enter a command for the system to load a specific parameter file from the tape. This file contains all the parameters used in this presentation of the task, such as Inter-stimulus Interval (ISI), Memory Set Size (MSET), use of visual mode versus auditory, etc. After the experimenter enters his selection the subject is presented the task. During the task presentation, all the error scores, reaction times, and other useful data are stored in files of the cassette tape containing all the collected reaction times, error scores, and various other parameters. The program then recycles to the experimenter's console and waits for another command. When the experimental session is over, the cassette tape is retrieved for preliminary data reduction and display.

In order to create a cassette tape containing the operating program and stimulus parameters, a microcomputer is provided that contains 2 floppy disk drives, mainframe, CRT terminal, printer, digital tape recorder, and Disk Operating System (DOS). Located on disks are several user programs that allow the experimenter/scientist to create parameter files. Also located on the disk is a program that contains the operating software for the WAD along with a linker. When the experimenter wants to create a parameter tape he links together the previously created parameter files to be used with the task and the WAD operating software. This newly created link file is then written out to the cassette tape.

During data reduction or analysis, the cassette tape containing the newly recorded data is placed in the tape transport and a loading program is run. This program creates files on the disk containing all the experimental data collected. The experimenter is then able to display the data on the CRT, print it out on the line printer, or submit the data to several data reduction or analysis programs.

SOFTWARE

The WAD software consists of several programs mentioned above. Most of the hardware drivers and controlling software are written in assembly language, but some of the complex data handling routines are written using Pascal. All of the data analysis software runs under the CP/M disk operating system (DOS). This DOS was chosen because many applications software packages and high level languages are designed to use CP/M for their I/O and file structures.

EXPANDABILITY

Since the main controlling software for the WAD is located at the beginning of each parameter tape and the source is on the floppy disks, it is very easy to modify. The experimenter simply makes his changes using the text editor and recompiles the program. When he makes a parameter tape the new controlling software will be included provided the file name was not changed. This provides the experimenter/scientist with a very versatile system that can be modified for custom applications and has the capability of adding new tasks. Since the peripherals provided are under software control, any sequence of operation can be programmed, thus allowing many different tasks to be included in the data base.

In addition, 16 channels of analog to digital (A/D) converters with interface are being installed. This will enhance the system by allowing it to sample up to six primary control surfaces from the NT-33A, or any other system/simulator. By arranging the data under software control, many derivations of the item-recognition task can be constructed.

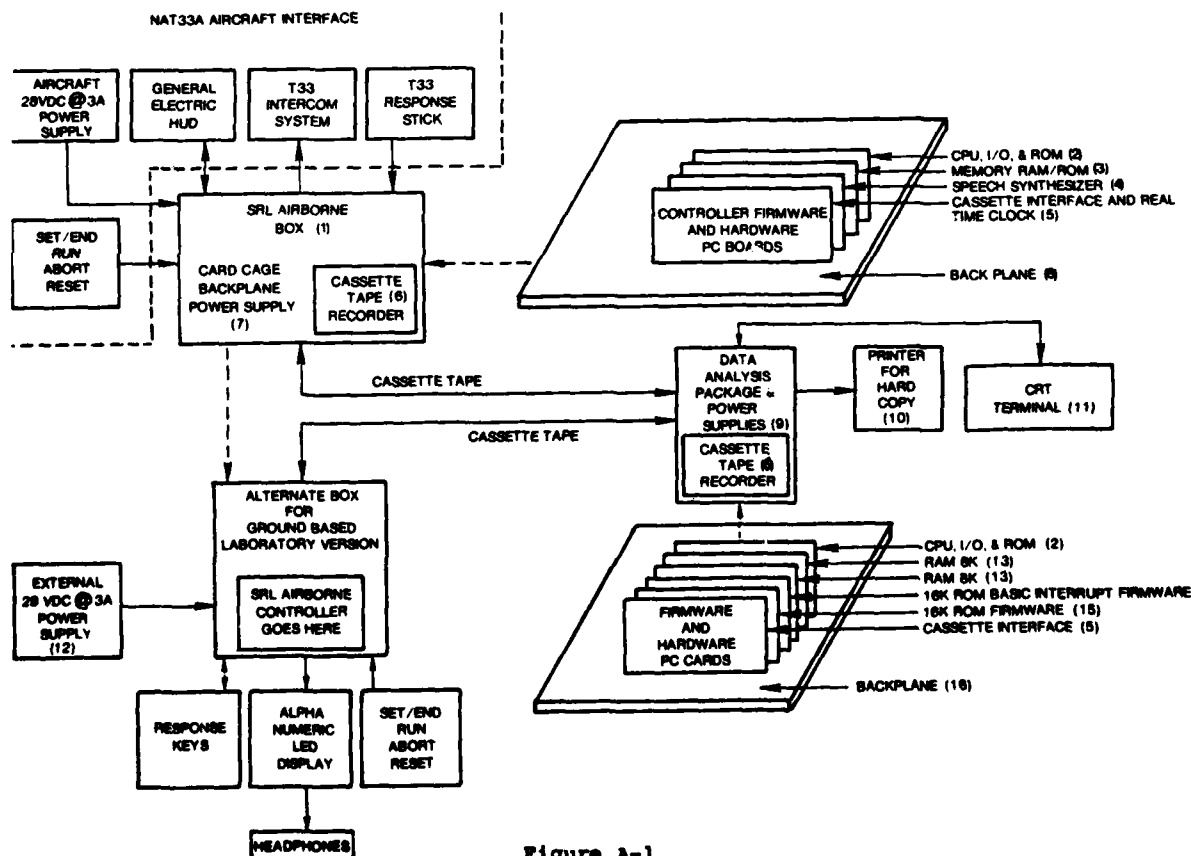


Figure A-1

TANKER AVIONICS AND AIRCREW COMPLEMENT EVALUATION

by

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Summary

This paper describes an effort to determine control and display criteria for operating SAC's KC-135 tanker with a reduced crew complement. The Tanker Avionics and Aircrew Complement Evaluation (TAACE) Program was a four phase effort addressing the control and display design issues associated with operating the tanker without the navigator crew position. Discussed are: the mission analysis phase during which the tanker's operational responsibilities were defined and documented; the design phase during which alternative crew station design concepts were developed; the mockup evaluation phase which accomplished initial SAC crewmember assessment of cockpit designs; and the simulation phase which validated the useability of the crew system redesign. The paper also describes a recommended crew station configuration and discusses some of the philosophy underlying the selection of cockpit hardware and systems.

PREFACE

Recognizing the potential for significant cost savings to the Air Force if the navigator position could be eliminated from the KC-135 tanker flight crew, the United States Air Force directed that a program be undertaken to determine the feasibility of replacing the navigator with avionics and/or other cockpit modifications (Ref. 1). In the Spring of 1978, the Air Force Wright Aeronautical Laboratories, Flight Dynamics Laboratory, started a two and one-half year effort aimed specifically at the crew system design issues associated with removing the navigator position from the crew but retaining the pilot, copilot, and boom operator. The work, known as the Tanker Avionics and Aircrew Complement Evaluation (TAACE) Program, was a four phase effort commencing with an analysis of the tanker's mission and associated crew responsibilities. The Program then progressed to a design phase during which several alternative crew system concepts were developed. During the third phase, a series of mockup evaluations were conducted to determine the crewmember acceptance of the different ideas, while the fourth phase accomplished a simulator validation of the findings of the previous mockup activity. The Program results indicated that operation with a reduced crew complement is a viable option if suitable equipment changes are made; specific crew station concepts and control and display subsystems were identified which offer the potential for operating the tanker without the navigator.

Additional engineering development is currently underway and a final determination of the feasibility of operating the tanker without a navigator has yet to be made. The following sections of this paper discuss the activities involved in accomplishing each of the four program phases, concluding with a brief philosophical overview of the approach used in performing the program.

1. PHASE I - MISSION ANALYSIS

The first ten months of the TAACE Program were devoted to documenting SAC's tanker mission and identifying the duties and responsibilities of each of the four flight crewmembers. The intent was to establish as complete a description of the entire system as possible; the vehicle, its subsystems, the mission tasks, and the operational context in which the system was employed. Heavy reliance for collecting this data was placed on in-flight observation of training and operational flights and crewmember interviews. A total of 25 in-flight observations were made, ranging from Combat Crew Training flights to European theater refueling exercises. During these flights, crewmembers were given opinion questionnaires to fill out aimed at obtaining subjective workload estimates as a function of both crew position and mission segment. Figure 1 summarizes the workload ratings for all crewmembers for all observation flights and permits a subjective comparison of the perceived levels of workload for selected segments of the tanker's mission.

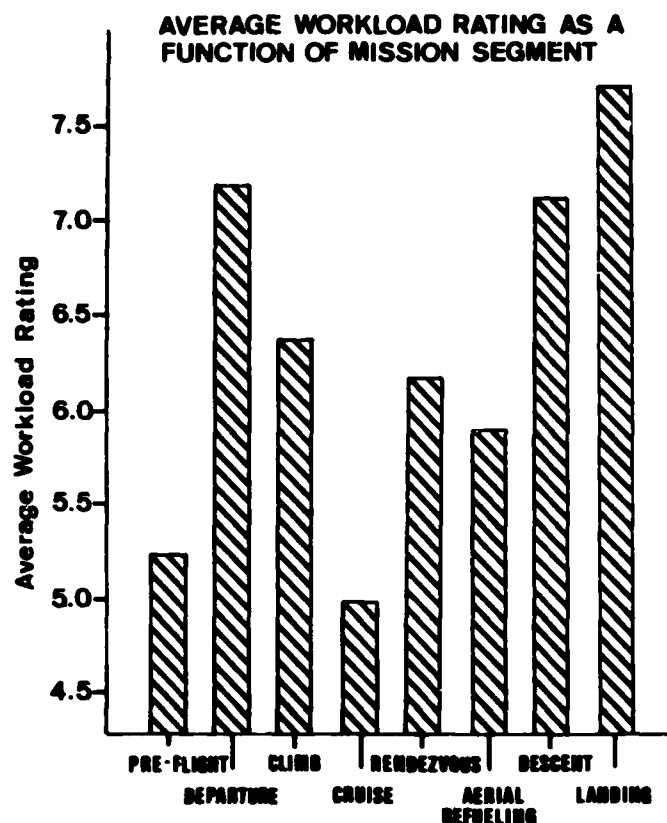


Figure 1. Average Workload Rating as a Function of Mission Segment.

In addition to this subjective workload assessment, a great deal of descriptive information was obtained during each flight identifying the activities engaged in by the crew during the different mission segments. This was done so that a complete statement of tanker operations and crewmember responsibilities was available to assure that necessary capabilities were not inadvertently eliminated from the new, three crewmember configuration. The descriptive information was collated and used to invent a hypothetical mission detailing an operational employment of the tanker. This document, known as the mission scenario, was drafted at Wright-Patterson AFB, and then carefully coordinated with Headquarters SAC personnel and operational crews to assure that it was realistic and conformed to the Command's views and needs. After several iterations, a version was established that was representative of the types of events encountered by the KC-135 during day-to-day operations. Included in the scenario for completeness were selected system failures, various weather conditions, and different levels of crew workload. A great deal of care was exercised in creating the scenario as it established the standard against which any new designs would be measured. It was realized that unless an accurate test of the new concept was available, little assurance as to the useability of the new system could be established.

The scenario was documented in three ways; by altitude profiles (Figures 2, 3, and 4) a time line, a portion of which is shown in Figure 5, and a narrative.

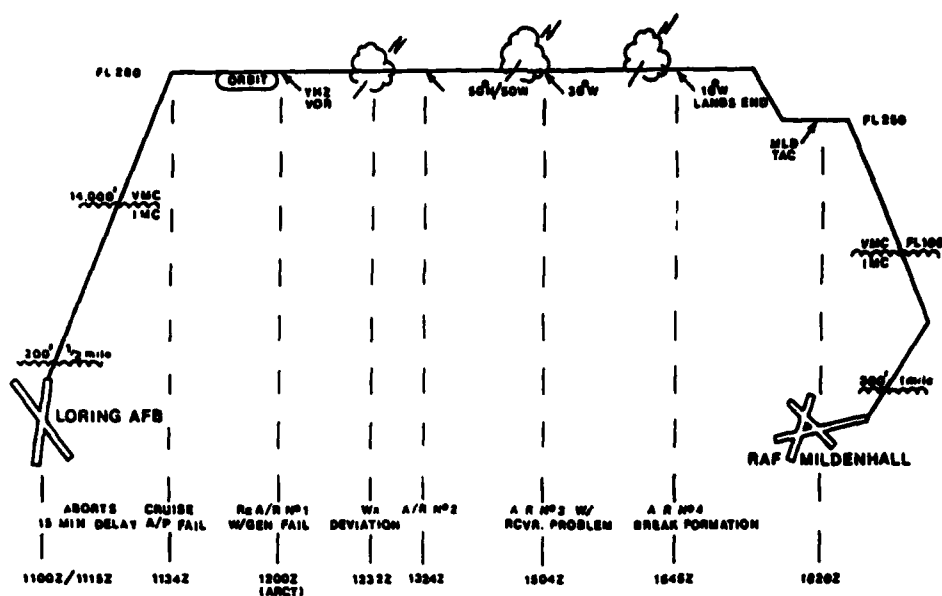


Figure 2. Profile of First Flight - Loring AFB to Mildenhall RAFB.

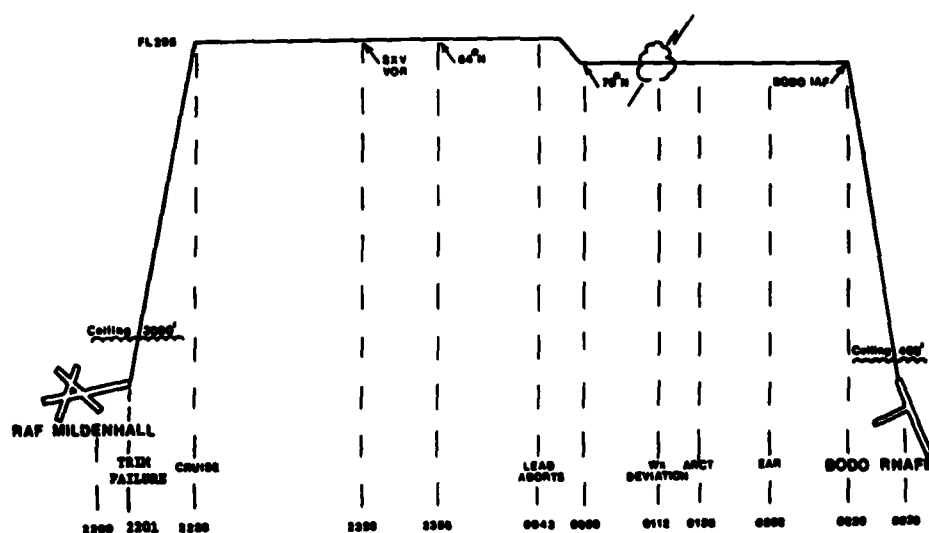


Figure 3. Profile of Second Flight - Mildenhall RAFB to Bodo RNAFB.

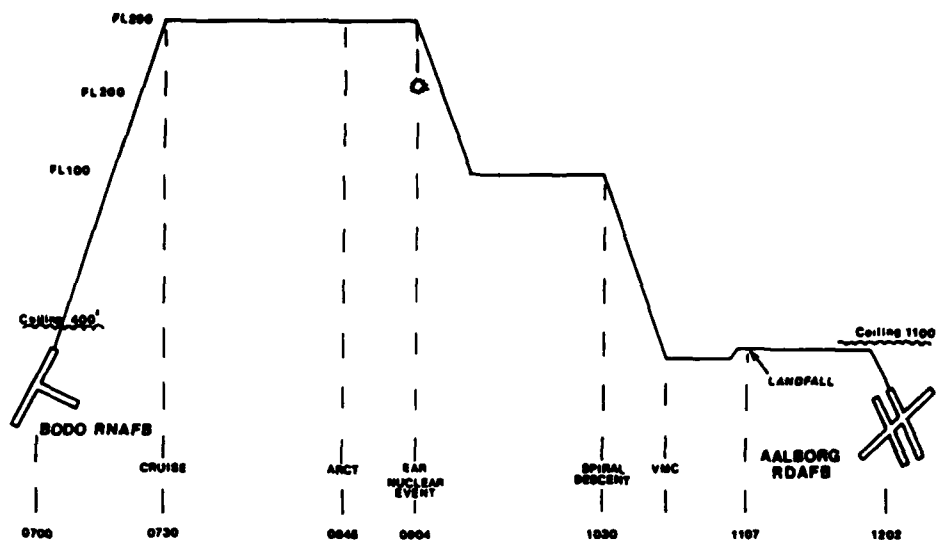


Figure 4. Profile of Third Flight - Bodo RNAFB to Aalborg RDAFB.

ELAPSED TIME	GMT TIME	PILOT	COPILOT	BOOM OPERATOR
02 06	1146	MONITORS AUTO PILOT HEADING AND ALTITUDE CONTROL CONFIRMS SYDNEY ETA // 1205	ACKNOWLEDGES MONICOM REQUEST FOR IFF IDENT AND TRAFFIC INFORMATION	DECODES HF MESSAGE
02 11	1151	MONITORS AUTO PILOT AND SLIGHT COURSE CORRECTION CHECKS WIND AND DRIFT	ACKNOWLEDGES ESSO 25 AIR PROGRESS	MAKES COMM LOG ENTRY
02 24	1204	MONITORS MAP DISPLAY POSITION NOTES FUEL STATE	NOTIFIES ESSO 25 FOR TURN PREPARATION OVER SYDNEY	MAINTAINS OUTSIDE VISUAL WATCH
02 25	1205	NOTES SYDNEY STATION PASSAGE TURNS ON COURSE WITH AUTO PILOT	NOTIFIES ESSO 25 FOR SYDNEY PASSAGE AND TURN MANEUVER ACKNOWLEDGES ESSO 25 AIR PROGRESS	UPDATES POSITION ON IN MAP MAKES ENTRY ON FUEL AND COMM LOG
02 26	1206	MONITORS AUTO PILOT ETA TO ST JOHNS GS TAS WINDS DRIFT AND PRESENT POSITION	ACKNOWLEDGES MONICOM TRAFFIC AND IFF CODE CHANGE MONITORS FUEL STATE MAKES ENTRY INTO NAV LOG	MAINTAINS OUTSIDE VISUAL SCAN

Figure 5. Portion of time-line identifying crew tasks during cruise segment.

Briefly, the scenario describes the events and tasks accomplished by a single tanker during three operational flights over a period of three days. The first flight is a fighter deployment to Europe supported by a five ship tanker force. The described tanker is briefed to be the number two aircraft in the tanker formation, but due to system malfunctions experienced during the take-off roll, must delay on the ground for minor repair. The resulting late departure generates out-of-the-ordinary navigation tasks, created in the scenario as the first major test of the system's ability to cope with unexpected situations. Eventually, the aircraft joins with the previously departed formation and proceeds to Europe. During the flight, various tanker system failures occur, as well as encounters with adverse weather and receiver refueling malfunctions. An uneventful IPR recovery in England terminates the first flight. The second flight is an Emergency War

Order (EWO) mission, in which the described tanker is number two in a two ship formation launched from Mildenhall RAFB to join with two B-52 bombers over the North Atlantic. During the cruise segment to the rendezvous, the lead tanker experiences unresolvable system failures requiring single ship completion of the remainder of the mission. Once again, tanker malfunctions dictate additional workload, including tanker control of the rendezvous with the receivers and minimum fuel landing at the recovery base. The third and final flight is also a two ship mission, launched from BODO AFB, Norway, to support tactical air operations in Eastern Europe. An extremely high workload situation is established during the orbit and subsequent refueling operations with the mission unexpectedly terminated by the detonation of a nuclear device somewhere in the vicinity of the aircraft. A complete description of the mission, including the entire narrative and time line, is provided in the TAACE Program Final Report (2). Figure 6 is an artist's overview of the entire scenario.

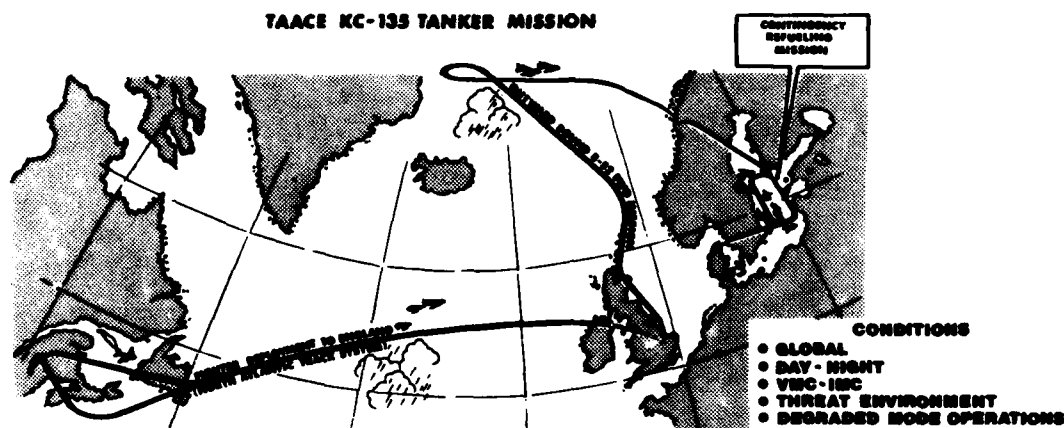


Figure 6. Overview of entire mission scenario.

2. PHASE II - CREW SYSTEM DESIGN

After thorough analysis of the scenario, a tentative list of crew station revisions was made identifying the elements of the existing system that might be altered in order to affect the elimination of the navigator from the crew. In addition, readily available systems and control and display components that would have to be added to the vehicle were also catalogued and their suitability assessed. This hardware oriented activity provided the transition to the second phase of the program, the development of specific design concepts for flying the tanker without a navigator.

The second phase of the TAACE Program dealt with the development of crew system concepts that would provide for operation of the vehicle, monitoring of subsystem's performance, accomplishment of the refueling tasks, and complete and safe accomplishment of the navigation job without the benefit of the navigator crewmember. It was clear from the outset that particular attention would have to be paid to the reworking of the navigation subsystem. However, since the level of automation and integration needed to eliminate the navigator from the crew was not known beforehand, three alternative crew station designs were developed. They differed from each other in several ways: the degree of change or update to the existing tanker; the amount of automation incorporated in the design; and the costs associated with retrofitting the fleet. These three designs were named the MINIMUM, MODERATE, and MAJOR updates.

The MINIMUM update (Figure 7) redesign was developed as the least expensive alternative to operating the tanker without a navigator.

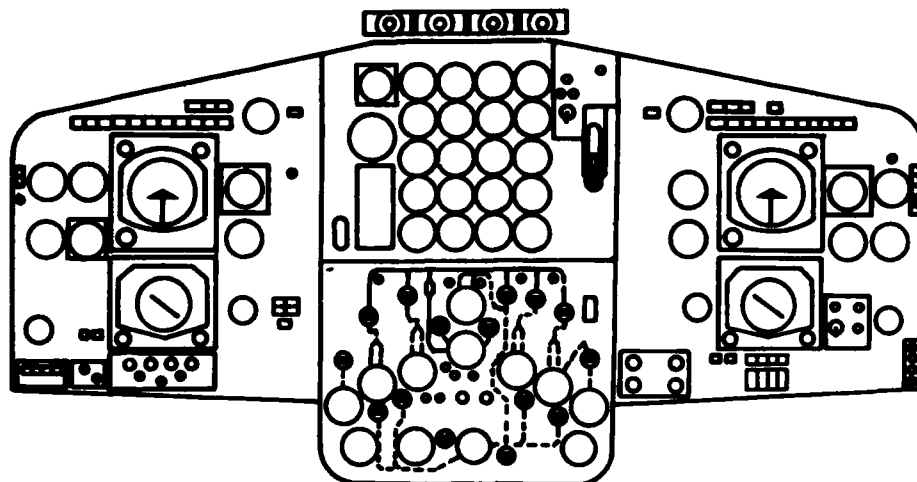


Figure 7. MINIMUM Update Redesign.

It incorporated very minor changes to the baseline configuration and is characterized more by the rearrangement of on-board controls and displays than by the addition of new systems. It was felt that the minimum update represented the least sophisticated (and least costly) concept with any chance at all of providing the necessary functions and capabilities compatible with a reduction in crew size. In this sense, it was one end of a sophistication/cost/capability continuum by which the three designs could be compared.

The MODERATE update (Figure 8) was developed as the most logical candidate, one having a moderate blend of the new systems, rearranged existing systems,

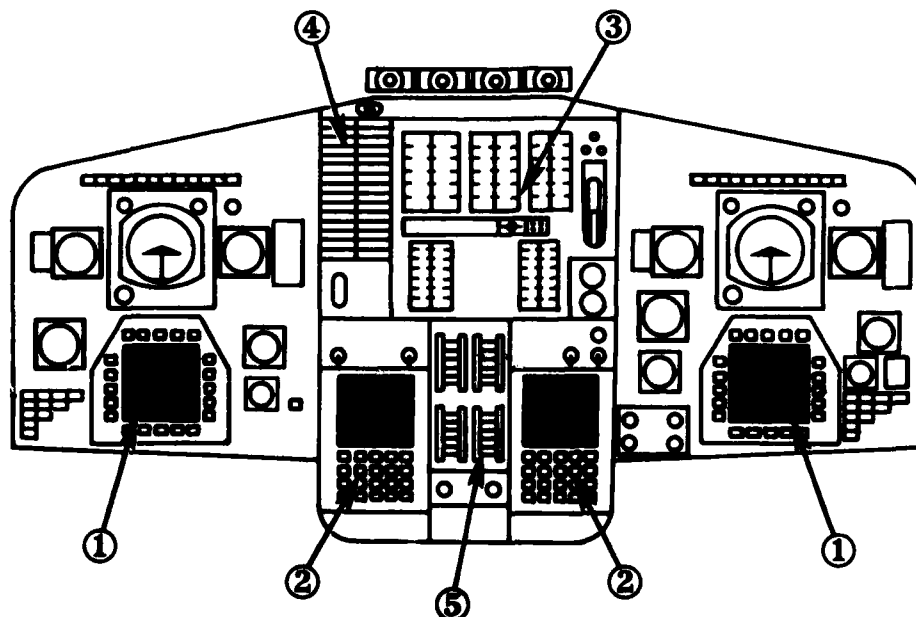


Figure 8. MODERATE Update Redesign showing (1) Pilot and Copilot Electronic HSI's, (2) Navigation Management Subsystem CRT/Keyboard Units, (3) Reconfigured Engine Instrument Panel, (4) New Caution/Warning Panel and (5) Fuel Quantity Instruments.

and modified crew station geometry. This design - characterized by the addition of several major cockpit subsystems including integrated caution and warning annunciator lights, vertical scale engine instruments, electronic displays to replace the electro-mechanical HSI's, and two electronic display/keyboard units (Figure 9) through which the crew interacted with the new navigation management of existing controls and display - was felt to provide the necessary level of crew support to assure successful mission completion.

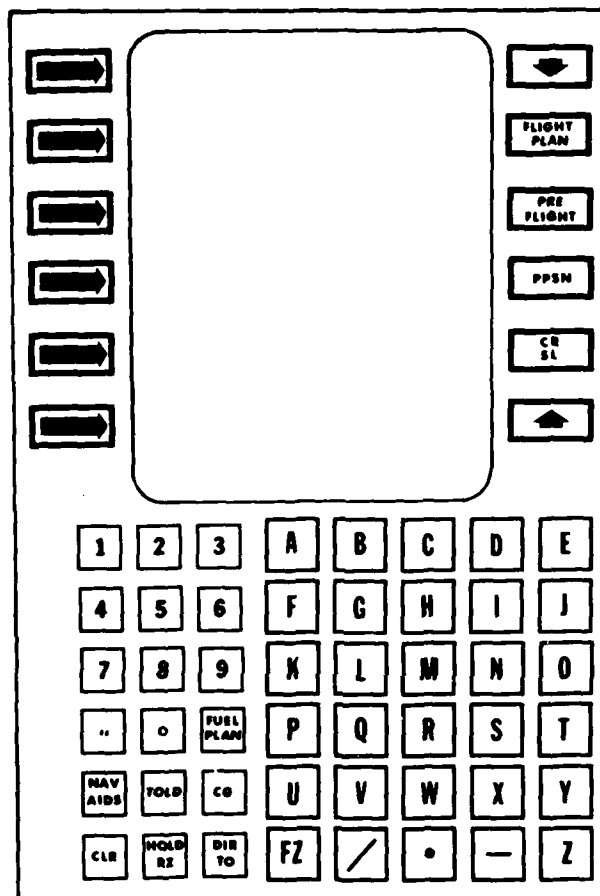


Figure 9. Navigation Management CRT/Keyboard Unit.

The third and final design, the MAJOR update (Figure 10) was developed to consider a configuration felt to be more than adequate to do the job.

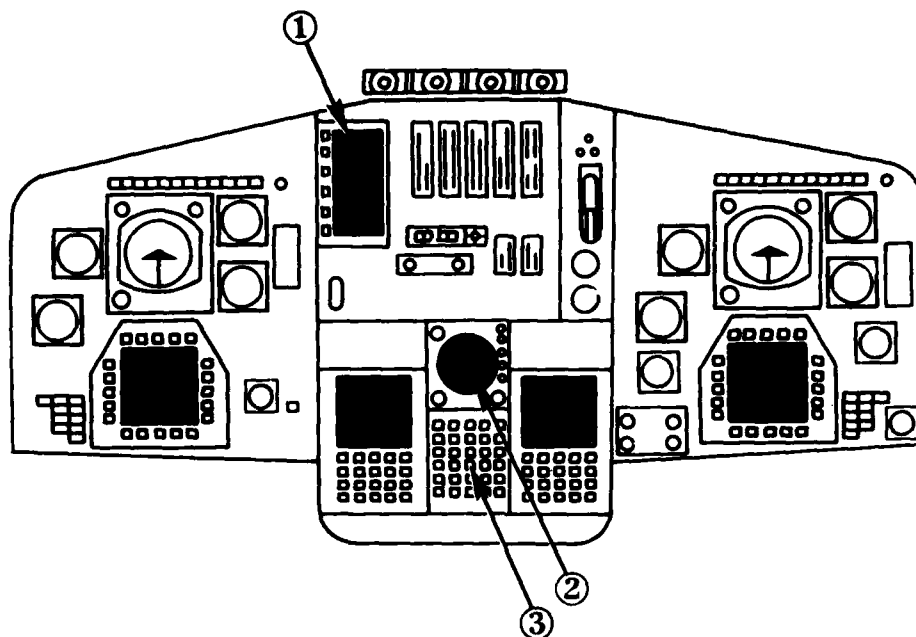


Figure 10. MAJOR Update Redesign showing (1) Automated Checklist Readout, (2) Dedicated Weather Radar Scope and (3) Fuel System Switch Matrix.

From the outset, it was assumed that the MAJOR update was more sophisticated than was absolutely necessary. In addition to the modifications advocated for the MODERATE update, the MAJOR update included a completely automated fuel management system, integrated tuning of all voice radios, and computer storage and electronic display of checklists and emergency procedures. In a sense, the MAJOR update represented the opposite end of the continuum from the MINIMUM update, the two bounding the design problem, thereby placing limits on the extremes of control and display sophistication to be explored. In the middle, representing what appeared to be a logical trade-off between the austerity of the MINIMUM update and the extravagance of the MAJOR update, was the MODERATE update.

The design phase of the TAACE Program was not confined to the development of the three designs on paper. As part of the process of creating the different configurations, a full-scale mockup facility (Figure 11) was constructed which was used to verify the suitability of control and display location, crew station egress and ingress, and overall crew coordination. The mockup was an accurate replica of the KC-135 cockpit and played a fundamental role in the design process. As the three configurations were evolving, each in its turn was laid out in the mockup and assessed for adequacy from the designers point



Figure 11. Exterior of full-scale mockup used during TAACE Program.

of view. Thus, during the course of the design phase, each configuration was continually examined and refined as appropriate. After the configurations were fairly well established, cockpit checklists and procedures were developed, an integral part of the design task, directed toward establishing crew roles/duties and efficient crew system functioning. Checklists and procedures are the operating instructions that inform the crew of the techniques for using the system during both normal procedures and emergencies, and operating procedures often represent a direct link between the design community and the user. During the TAACE Program, cockpit procedures were extremely important; SAC has established very specific ways of performing its mission and the already-in-existence operating procedures for the tanker in the context of the refueling mission often established as definitive a set of design requirements as did the crew size issue itself.

When the point of diminishing returns was reached - the point where iterations to the designs produced very little real change - the program progressed to the third phase, the mockup evaluation of the three configurations.

3. PHASE III - MOCKUP EVALUATION

The third phase of the TAACE Program performed an initial set of evaluations of the three designs; an initial assessment of the utility and pilot acceptability of each of the three configurations from the operator's point of view. The mockup evaluation returns the focus of activity to the user, providing another opportunity for user inputs to the development process. The intent is to create a structured situation during which operationally experienced crewmembers are given the chance to assess how well the design can support safe and effective accomplishment of the mission.

A total of nine fully-qualified, operationally experienced SAC tanker crews participated in the mockup evaluation. The general sequence of activities for each crew included attending ground school, receiving realistic mission briefings, "flying" in the mockup, filling out opinion questionnaires and attending debriefings. Three crews participated in the evaluation process at one time. Starting on a Monday morning, and finishing on a Friday evening, it typically took five days to complete all scheduled activities. Thus, a total of three weeks were needed to collect all the mockup evaluation data. On the first day of each week, three crews were introduced to the TAACE Program at which time the goals and objectives of the work were explained. This rather informal session helped establish rapport with the user and generate enthusiasm for the process wherever possible.

It was pointed out that the mockup activities to follow were a significant departure from the traditional cockpit design process, and that the significance was due primarily to the user's involvement and willingness to "role play" during upcoming mockup flying sessions.

Following the orientation briefing, the crews attended several hours of ground school, classroom type sessions during which the cockpit designs were discussed and explained. A great deal of time was spent briefing the new systems and their operating procedures; line crews are often not familiar with the new concepts or hardware and an effective evaluation demands that the crewmembers thoroughly understand how the equipment operates. Ground school is a relatively formal give and take of information with the crews learning the new configurations and how the equipment is intended to help them perform the mission, while passing along insight into good and bad features of the different ideas. Often, unanticipated uses for features of the design are discovered while deficiencies or illogical procedures may also be noticed. Frequent use is made of the mockup to familiarize the crewmembers with the location of equipment; during the flying sessions they are asked to move their hands from control to control in order to assess reach envelopes and accessibility, and awareness of the location of equipment facilitates this assessment.

Actual role playing in the mockup took place after the ground school sessions were completed. As was mentioned earlier, nine SAC crews participated in the mockup evaluation phase of the program. However, for the activities associated with the actual mockup role playing, each crew was treated individually. Mission briefings began the process with each crew being given flight, weather, communications, formation and refueling information in a manner similar to standard SAC tanker operational briefings. The intent was to create a mind set within the crewmembers such that once inside the mockup, they were thinking along mission lines and evaluating the designs in the context for which they were intended. Each crew received three different mission briefings, one for each of the three flights developed during the mission analysis phase of the program. During the briefings, the crews were encouraged to ask questions about the mission and to make sure they understand the job to be done. They were informed that they were expected to perform all communications tasks that would ordinarily take place during the mission, maintain an awareness of their navigation situation, calculate all parameters e.g., take-off and landing data, estimated times-of-arrival, etc., and generally perform all crew station duties demanded of the mission or the systems in the crew station. Since some emergencies were to occur during each flight, the crews were also reminded of their responsibility to be familiar with all checklists and emergency procedures.

After each mission briefing the crew entered the mockup, climbed into the seats, and started the role playing exercise. They donned headsets and communicated over a functional intercommunications system, beginning the process with the appropriate checklist for the mission being flown. Outside the mockup, there was an experimenter's console manned by two test engineers responsible for monitoring the mockup session and providing external voice communications in response to either mission situations or crew initiated commands. Typically, the test engineers assumed the voice communications for such external agencies or personnel as ground control, tower, departure control, Air Traffic Control, SAC Command Post, fire guard on the ground, and other aircraft in the formation.

The test engineers also paced the mockup flight by providing indications of mission progress in the absence of functional flight or navigation instrumentation. For example, after the crew had completed the "Line-Up" checklist and simulated a take-off, a test engineer, speaking as Departure control, would call the aircraft and say that radar contact had been established. This sort of feedback helped keep the mission moving and the crew oriented, and was provided throughout the role playing exercise. Finally, the test engineers moved the flight ahead of its normal time line in order to eliminate long uneventful segments of the scenario where, because of the lack of operable equipment, the crewmembers would not be learning anything new about how the system was intended to operate. To effect a "move ahead", a test engineer would inform the crew that they had just completed a specified series of tasks and that the flight was being moved ahead to test the useability of the system under another set of conditions. The crew would then be briefed on the new conditions; e.g., altitude, heading, airspeed, GMT, weather conditions, current agencies in communications contact, and upcoming events, such as passing a specific radio aid to navigation. During the first flight, for example, the crew was permitted to accomplish several cockpit checklists, prepare for and execute the take-off, and join-up and then establish themselves mentally at cruise altitude before the first "move ahead" took place. The flight was then advanced to a position over the North Atlantic, just prior to one of the Mid Atlantic air refuelings. Approximately 30 minutes of air refueling activity was performed after which the flight was moved ahead again, this time to a point approximately 30 minutes prior to touchdown at Mildenhall RAFB. The crew was permitted to complete the final segment in real time, making radio contact with all the necessary controlling agencies in England, performing necessary descent and before landing checklists, and simulating the approach and touchdown.

The overall role playing exercises encompassed a total of twenty-seven flights. Every crew flew each of the three mission flights once, using one of the three designs; thus, each crew flew all tasks and used all designs, but did not experience all the possible combinations of design coupled with flights. Over the course of the total mockup phase however, each of the nine possible combinations occurred three times.

Immediately after the flying sessions, the crews were handed questionnaires asking their opinion about the useability of the design just flown to do the job just completed. The intent was to not only determine which of the three designs was best suited to a removal of the navigator, but how, if at all, their suitability varied as a function of mission tasks.

The mockup flying and subsequent evaluations provided by the SAC crews identified both good and bad features of all three designs, resulting in the development of a fourth configuration, a composite of elements from each of the original three. The detailed results of the Mockup phase are documented in an Air Force Wright Aeronautical Laboratories, Technical Report, AFWAL-TR-80-3030 (Vol. 1) (Ref. 2). A summary of those results is provided here.

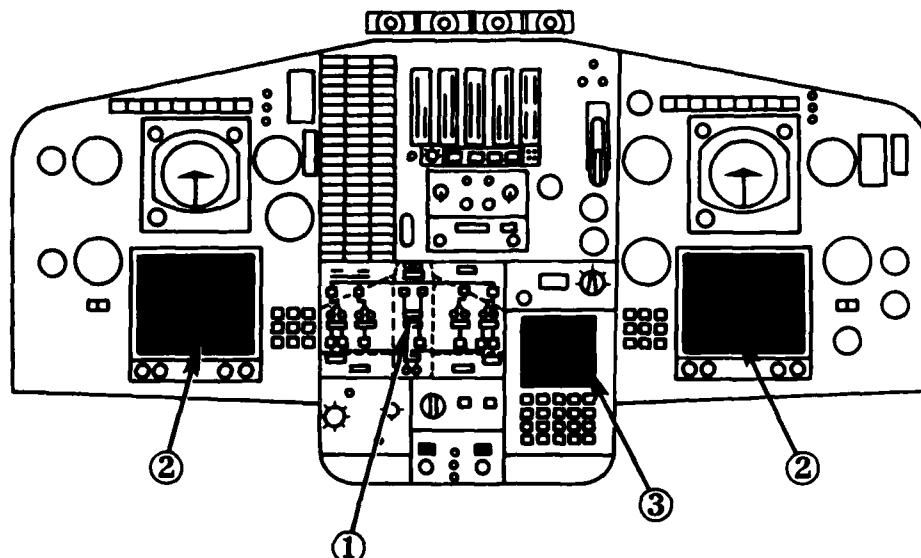


Figure 12. COMPOSITE Redesign. Note (1) Schematic representation of fuel system, (2) retained pilot and copilot electronic HSI's, and (3) Navigation Management CRT/Keyboard Unit. Second unit is installed on an isel stand, aft of throttles, not shown.

The desired COMPOSITE design (Figure 12) was characterized by a navigation management system similar to the one defined in the MODERATE update, capable of displaying at least six upcoming waypoints at a time, computing take-off and landing data, storing holding or rendezvous patterns for air refueling operations and generating flight plan data such as time-to-go, or distance-to-go. None of the fuel management concepts included in the original three designs were judged suitable by the crews. Instead, a reduced version of the existing tanker fuel panel, with essentially the same capabilities as the existing panel, is included in the COMPOSITE. The most significant feature of the composite design is the electronic display replacement for the electro-mechanical HSI. This device displays, at pilot discretion, conventional horizontal situation data (Figure 13), computer generated map data (Figure 14), weather radar information (Figure 15), holding or rendezvous patterns (Figure 16 & 17), and other information typically provided by the navigator. The electronic HSI's, coupled with the navigation management subsystem, comprise the heart of the avionics needed to operate the tanker without the navigator crew position. The management system computes navigation data, manages some of the navigation radios, and generally performs the calculations accomplished by the navigator, while the electronic displays present to the pilot and copilot the information generated by the computer.

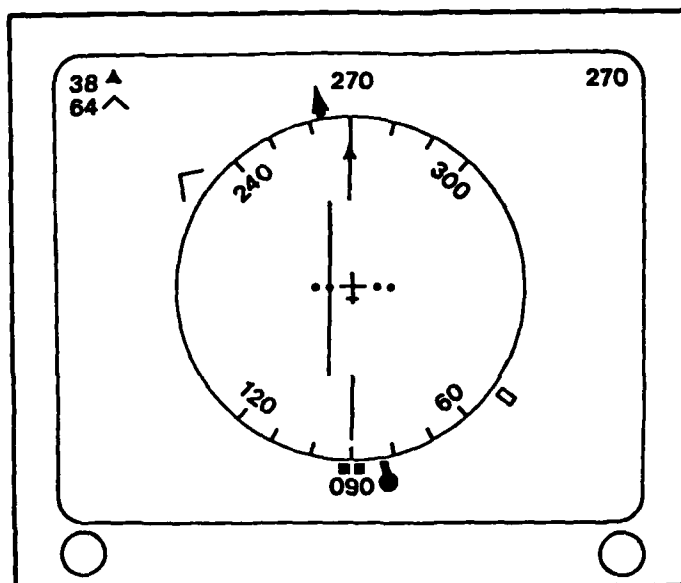


Figure 13. Electronic HSI, showing conventional horizontal situation information.

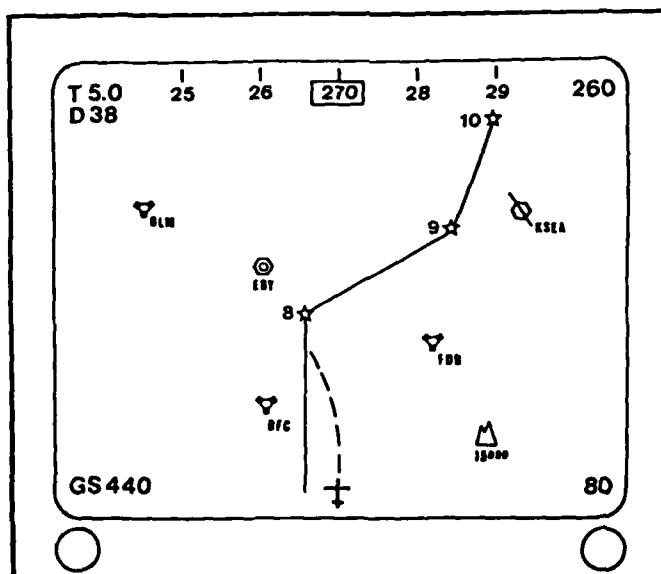


Figure 14. Electronic HSI, showing map format. Parameters shown, clockwise from upper left-hand corner, are Time (T) and Distance (D) to next waypoint, current aircraft heading (270), course between last waypoint and "To" waypoint (260) map range in nautical miles (80) and current ground speed (GS).

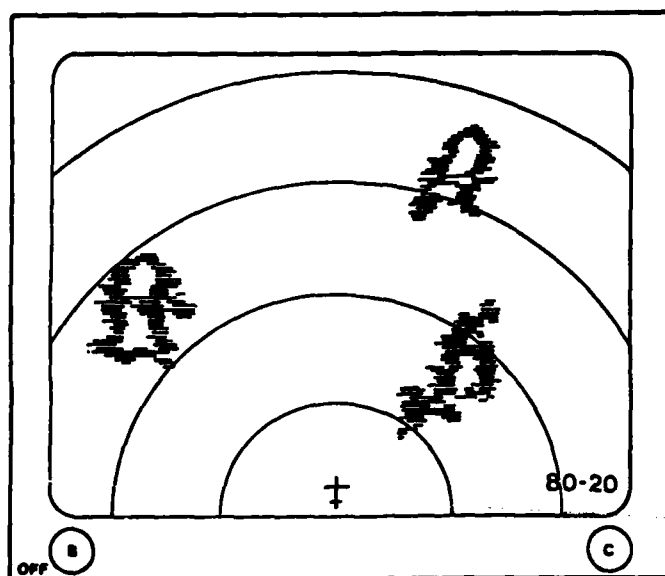


Figure 15. Electronic HSI, showing, weather radar information.

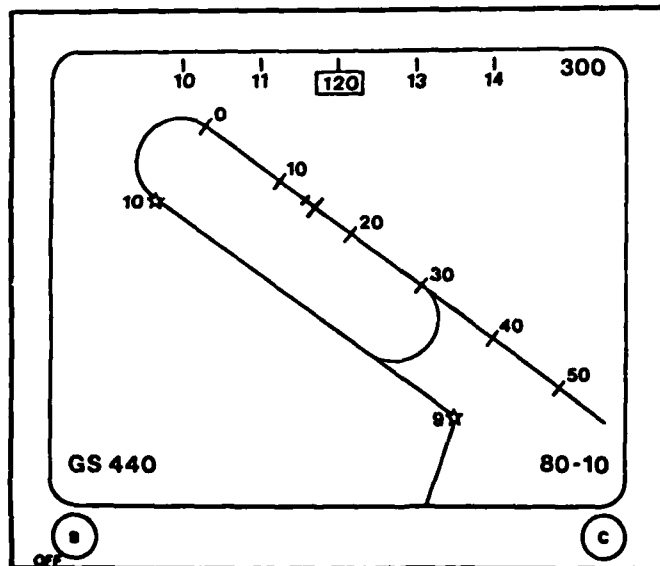


Figure 16. Electronic HSI, showing holding pattern information.
ORBIT shown is computer generated, based on information
supplied by the crew.

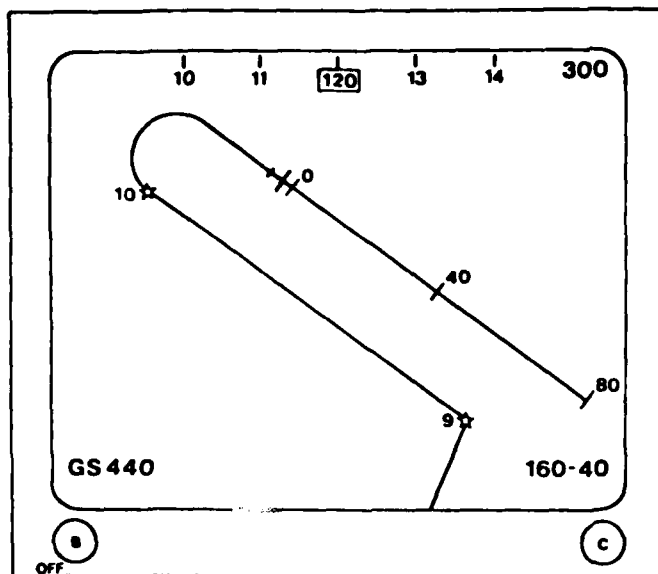


Figure 17. Electronic HSI, showing air refueling rendezvous information. Note airplane symbol and 40 and 80 range ticks. Range ticks represent distance from airplane symbol, and are used to anticipate tanker 180° turn to lead receiver along refueling course.

At this time in the program, a candidate avionics package and crew station configuration had been developed, based on the using commands evaluation of several alternative crew system concepts. A paring down process was taking place, having started during the design phase, where obviously unacceptable ideas had been eliminated, and continuing through the mockup exercise where additional assessment took place. The last phase of the TAACE Program accomplished the final paring down of ideas - fine-tuning the COMPOSITE design.

4. PHASE IV - SIMULATION VALIDATION

In general, the simulation work performed to validate the crewmember acceptability of the COMPOSITE design followed the same procedures employed during the mockup activity; SAC crewmembers were obtained to "fly" the system under simulated conditions, questionnaire data was obtained to record crewmember opinion, and a final set of recommended crew system control and display design criteria were generated.

The simulation facility used for the TAACE Program consisted of a cockpit cab (Figure 18), a visual projection system, a test engineer's console, a simulated boom operator's console, and supporting computer systems. The simulator cab was a geometric duplicate of the KC-135 cockpit outfitted with operable flight instruments, flight controls, lighting, communications radios, and navigation management subsystem (Figure 19).

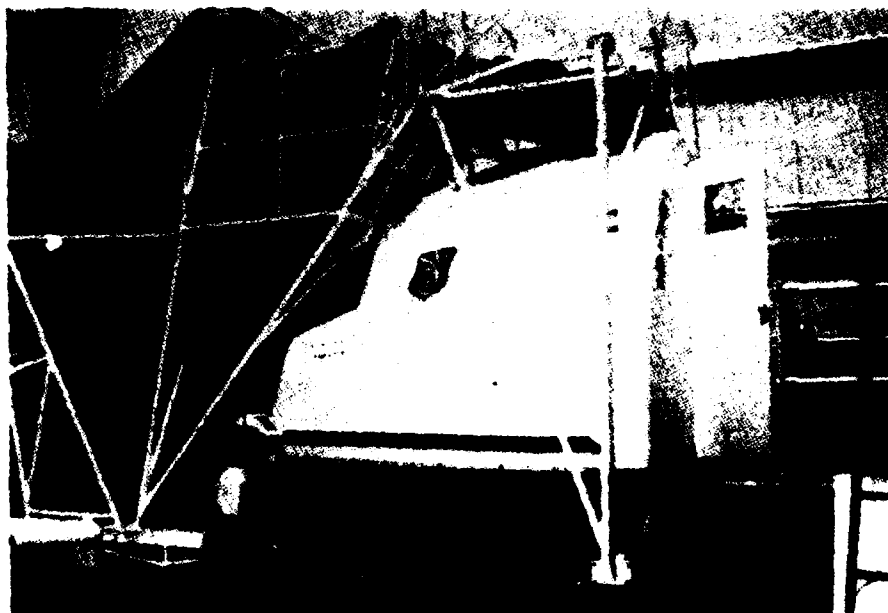


Figure 18. Exterior of simulator cab used during TAACH program.

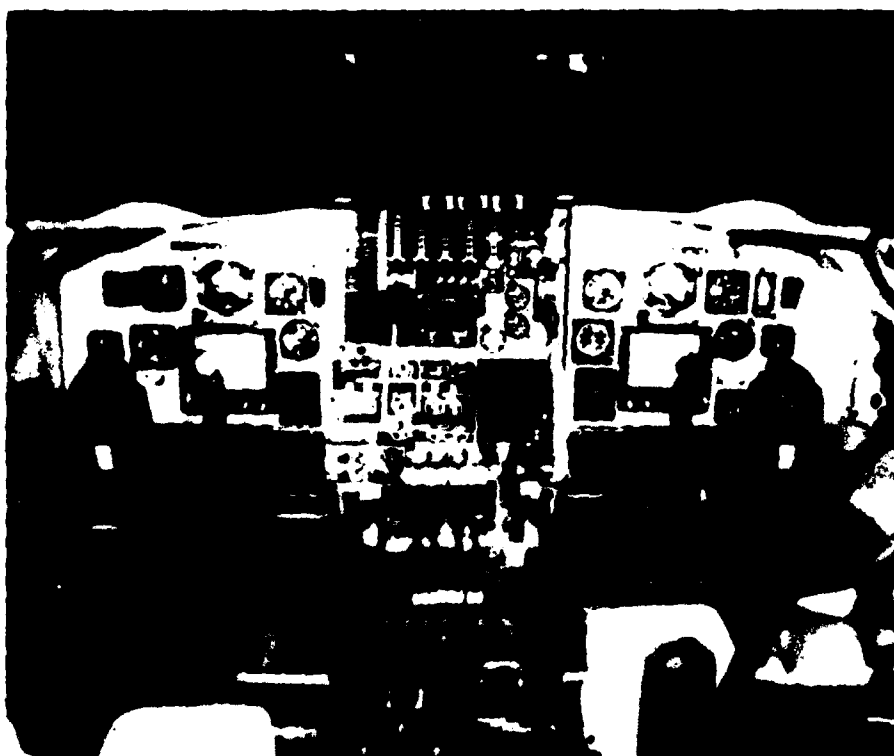


Figure 19. Interior of simulator cab configured with "COMPOSITE" design.

The crew could program any flight plan into the navigation system and through proper switch selection have relevant navigation data appear on the electronic HSI and flight director. The crew could then fly the flight plan and have computed for them pertinent navigation information. The system also displayed ground speed, true airspeed, time and distance to go to future waypoints, holding and rendezvous patterns, and other data deemed necessary as a function of the mockup evaluation work. To enhance the realism of the simulation, environmental conditions of day, night, and engine sound were provided along with a visual presentation of airport features for take-off and departure operations. The test engineer's console fulfilled the same functions as did the console used during the mockup work, with the addition of cockpit repeater displays to show information selected by the crew. Finally, a boom operator's console was fabricated to provide the boom operator, who participated as a member of the crew, with tasks to perform which simulated his activities during the air refueling segments of the flight.

The simulator sessions, flown by four crews not previously involved in the program, were conducted in the same way as the mockup sessions with each crew receiving mission briefings, entering the cab, flying the mission, and completing questionnaires. Since the real world flying task was simulated, the pilots, in addition to their mission responsibilities for navigation and subsystem monitoring, also had to fly the airplane. Thus, the single biggest difference between the mockup and simulation phases was the increased workload levied upon the crew, and hence, a more valid assessment of the design's useability. Another difference was the availability of objective system performance data. Prior to the simulator flights, the optimum mission profile consisting of headings, altitudes, arrival times, etc., was programmed into the computer for comparison with the crew generated values for the same parameters. This data was then analyzed to augment the pilot questionnaire data in making decisions about the suitability of the avionics systems flown by the crew.

In contrast to the large differences between the MINIMUM, MODERATE, and MAJOR crew stations that were evaluated during the mockup work, resulting in the COMPOSITE design, the simulation phase attempted to assess the relative goodness of much more subtle crew system alternatives. For example, after the mockup work, it was unclear as to exactly how much flexibility the crew should have in selecting for display raw navigation sensor data. The mockup evaluation was simply not sensitive enough to determine this. Consequently, during the simulator flights the crews, although always using the same equipment, were given different levels of capability with which to operate. During one leg of a flight, for example, they might fly with only one navigation management system electronic display/keyboard unit operable, while at other times, have access to two units. Thus, the simulation phase was a continuation of the paring down process started during the design phase, with the level of emphasis placed upon finer details of equipment operational capability or arrangement.

The alterations in the COMPOSITE design needed to make it acceptable to the SAC crewmembers who evaluated it were not nearly as extensive as those made to the MINIMUM, MODERATE, and MAJOR designs to generate the COMPOSITE configuration. As expected, changes dealt primarily with details of display format, information content, or of the navigation subsystem. For example, it was felt that the Bearing Distance Heading Indicator should have the capability to display either TACAN bearing or flight plan waypoint bearing, as selected by the pilots; that when radar imagery was displayed on the electronic HSI certain navigation parameters be retained in the corners of the display; and that waypoints be retained in the flight plan until erased by the crew rather than eliminated automatically as used.

5. CONCLUDING REMARKS

The TAACE Program is significant because it demonstrates an objective, structured process for dealing with the very complex issues of crew system design and evaluation. Figure 20 overviews this process, starting with the mission analysis, progressing to the preliminary design phase, and moving through the various levels of user-in-the-loop evaluation.

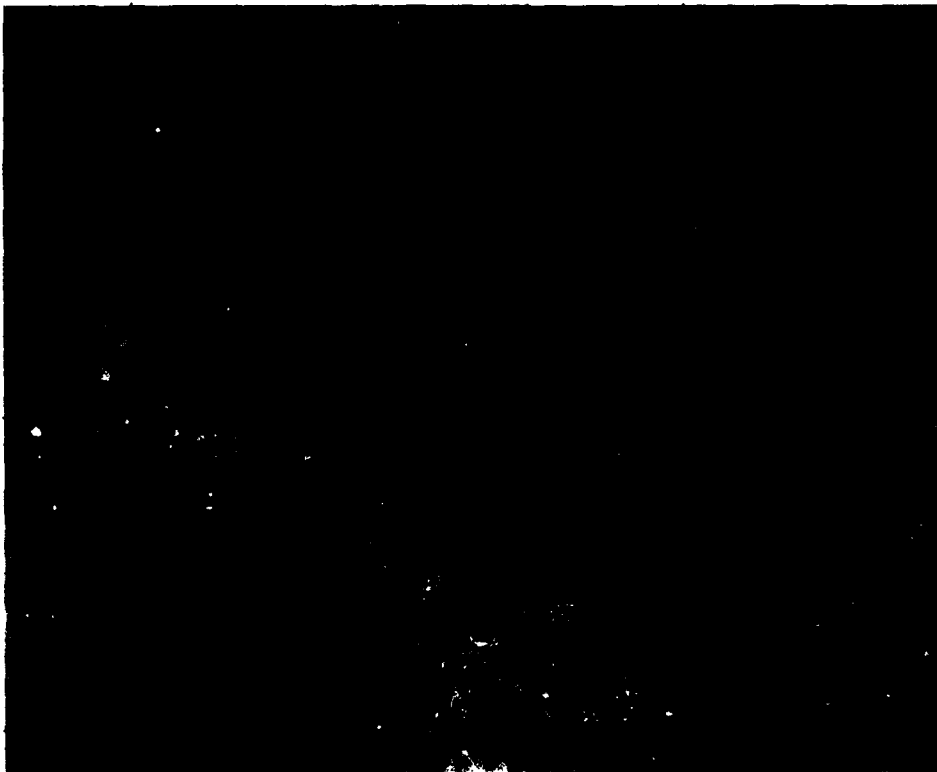


Figure 20. Crew system design process, showing major activities pursued during design and evaluation of new cockpit.

It is important to note the sustained reliance upon the user throughout the entire methodology, from the intense interface during the development of the design scenario to the mockup, simulator, or flight test work. It is also important to note the continued use of a validated, comprehensive scenario. At the outset, the scenario represents a definition of the problem being solved by the evolving crew system. Later in the process, it represents the criteria against which the design's useability is measured. Finally, the method provides for the collection of subjective pilot opinion data, objective system performance data, and other factors that can all be brought to bear on the decision making process. This was the approach used in the TAACE Program and it has proved compatible with the other on-going processes currently in use within the United States Air Force for developing and procuring new weapon systems.

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F/A-18 HORNET CREW STATION
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ABSTRACT

The F/A-18 Hornet Crew Station represents a considerable step forward in the application of integrated controls and computer controlled displays to the reduction of pilot workload and enhancement of mission success. The Hornet crew station design requirement was to essentially provide the capability contained in both the F-4 and A-7 weapon systems so as to perform both the fighter and attack roles, make it operable by one pilot, and increase mission reliability by a combination of improved hardware reliability and functional redundancy.

To put this requirement in perspective, the F/A-18 cockpit has 40% less usable area than any of its contemporaries. This area constraint necessitated extensive integration of the weapon system controls and displays. The resultant crew station features four multipurpose cathode-ray displays driven by two mission computers, an integrated upfront control panel, and numerous automatic functions on the "stick and throttle". This paper describes the rationale leading up to the configuration and presents a few examples of the one-man-operability features of the Hornet and how they would be used by the pilot. The crew station design was generated and validated by a vigorous process of analysis and simulation and is currently undergoing flight evaluation in eleven Hornet Aircraft at the Navy test facility at Patuxent River, Maryland.

INTRODUCTION

The Navy and Marine F/A-18 Hornet strike-fighter (Figure 1) being developed by McDonnell Douglas uses integrated controls and four computer aided displays to allow the pilot to perform both the fighter and the attack roles of the F-4 Phantom and A-7 Corsair from one cockpit. No internal hardware or software reconfiguration is necessary to switch fighter and attack roles. The role the aircraft will perform is determined solely by the external sensors and weapons loading and in fact, the Hornet can be configured to carry missiles, bombs, and gun ammo to perform the combined strike/fighter mission. This dual role capability is made possible by the use of multi-function displays with programmable switches surrounding each display, a programmable Up-Front Control that integrates many previously separate control and sensor panels and the implementation of numerous software controlled computers and microprocessors distributed throughout the various elements of the weapon system. One-man-operability was of paramount concern during the weapon system definition and integration phases and it was validated by a continuing series of pilot-in-the loop simulations at the McDonnell simulation facility.



FIGURE 1
F/A-18 HORNET

COCKPIT SIZE

The quest for good aerodynamic performance, fishbowl visibility, and minimum weight resulted in an airframe whose cockpit instrument panel and console area was 40% less than contemporary aircraft such as the F-4, A-7, or F-15, yet there were more systems to control and display in that smaller area. It was clear that to achieve one-man-operability of the numerous sensors and weapons on board, maximum advantage had to be taken of the recent trend toward programmable digital weapon systems and computer aided control and display techniques, human factors analysis, simulation, and functional automation.

APPROACH RATIONALE

The Cathode Ray Tube (CRT) was chosen as the display medium for the three identically formatted indicators shown in Figure 2. The CRT has undergone steady design improvements during the past 40 years

and presently offers the best combination of contrast and resolution in bright sunlight. Acceptable reliability can be achieved after a combination of vibration and burn-in cycles. These multi-purpose displays, in conjunction with the Head Up Display (HUD), provide the pilot with all essential flight information for air to air, air to surface, and navigation phases of the mission.

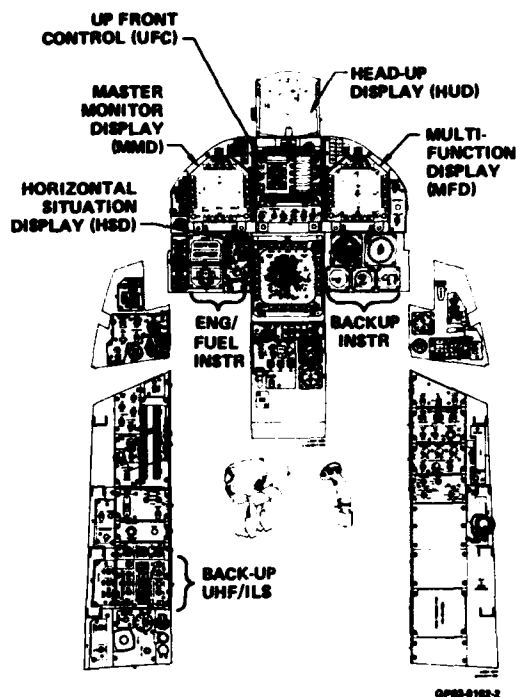


FIGURE 2
FIA-18 CREW STATION LAYOUT. MORE FUNCTIONS IN
40% LESS SPACE THAN CONTEMPORARY AIRCRAFT

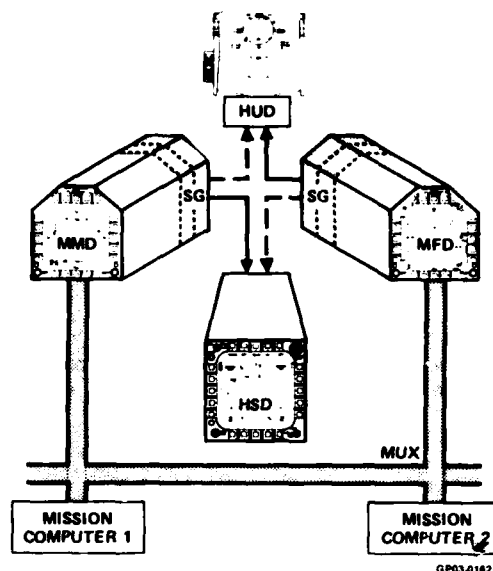
The HUD is the primary flight instrument for weapon delivery and navigation including manual and automatic carrier landing modes. All essential flight data such as speed, altitude, heading, attitude, alphanumeric cues, and steering commands are projected on the HUD combiner and focused at infinity for easy assimilation by the Pilot. The Multi-function Display (MPD) is the primary sensor display for radar attack, radar mapping, and backup for the Master Monitor Display (MMD). Superimposed on the sensor data is own-aircraft data such as attitude, speed, altitude, weapon status, and other alphanumeric cues. This reduces pilot scan time and allows search-through-reattack segments to take place on one display. The MMD is the primary warning, caution, EO and IR sensor, armament, built-in-test, and scratch pad display. The Horizontal Situation Display (HSD) presents CRT generated plan-view navigation information superimposed on a color film-projected moving map for easy navigation by the pilot. The HSD improves target finding accuracy during attack missions, simplifies navigation updates and radar map matching, and provides growth for display of other tactical data such as EW, electronic order of battle, navigation segments, and approximately 200 filmed data frames relating to aircraft systems.

Direct benefits of multiple CRT display of flight parameters, armament control, navigation, and other conventional parameters are: 1) Pilot scan times are reduced because sensor, weapon, and own-flight information is grouped together as required on each display; 2) An armament panel and more than a dozen low reliability, electro-mechanical servoed instruments have been deleted from the aircraft, reducing life cycle costs and freeing valuable cockpit space; 3) Mission reliability is enhanced because each of the display formats can be presented elsewhere thus precluding a single and even dual display failures from causing a mission abort.

The lower left corner of the instrument panel contains engine and fuel instruments necessary for pilot monitoring during aircraft self-start on battery power. The lower right corner of the instrument panel contain pneumatic standby airspeed, altitude, and vertical speed indicators and a 3" Attitude Director Indicator (ADI) with a self contained gyro for use in the unlikely event of total power or display loss.

The displays are mechanized (Figure 3) such that the MMD and MPD are identical and interchangeable black boxes thus reducing unit recurring costs and logistic support. Each contains symbol generators capable of driving two or three displays depending on the complexity of the modes. Thus either the MMD or the MPD can drive itself, the HUD, and essential data on the HSD in a backup mode. This dual drive feature provides a significant reliability improvement for the primary flight instrument function (HUD) and allows the pilot the tactical flexibility and mission reliability of putting sensor data where he wants it. The two seat trainer version (TF-18) uses three repeater type CRT displays in the rear seat which display information corresponding to their counterparts in the front seat. These hardware identical repeaters use the same modules contained in the front end of the MMD/MPD, further reducing life cycle costs.

FIGURE 3
F/A-18 DISPLAYS BLOCK DIAGRAM. MMD OR MFD
CAN DRIVE UP TO THREE DISPLAYS



ONE MAN OPERABILITY

The one-man-operability problem was approached with a clean slate. The small cockpit, numerous sensors to control and display, the Navy's new look in reliability, maintainability, and lower ownership costs required a fresh, integrated approach to the cockpit design. Five years of effort went into the cockpit design starting with mission analysis and simulation and ending with flight verification by a twelve member Navy/Marine and MCAIR flight team.

The problem was broken down into three major workload areas: 1) Time-critical weapon and sensor management during combat; 2) COMM, NAV, and Ident (CNI) management during all phases of flight, especially low visibility carrier operations; 3) Moding and miscellaneous requirements, usually not time critical but nevertheless cockpit space and task consumers in previous aircraft.

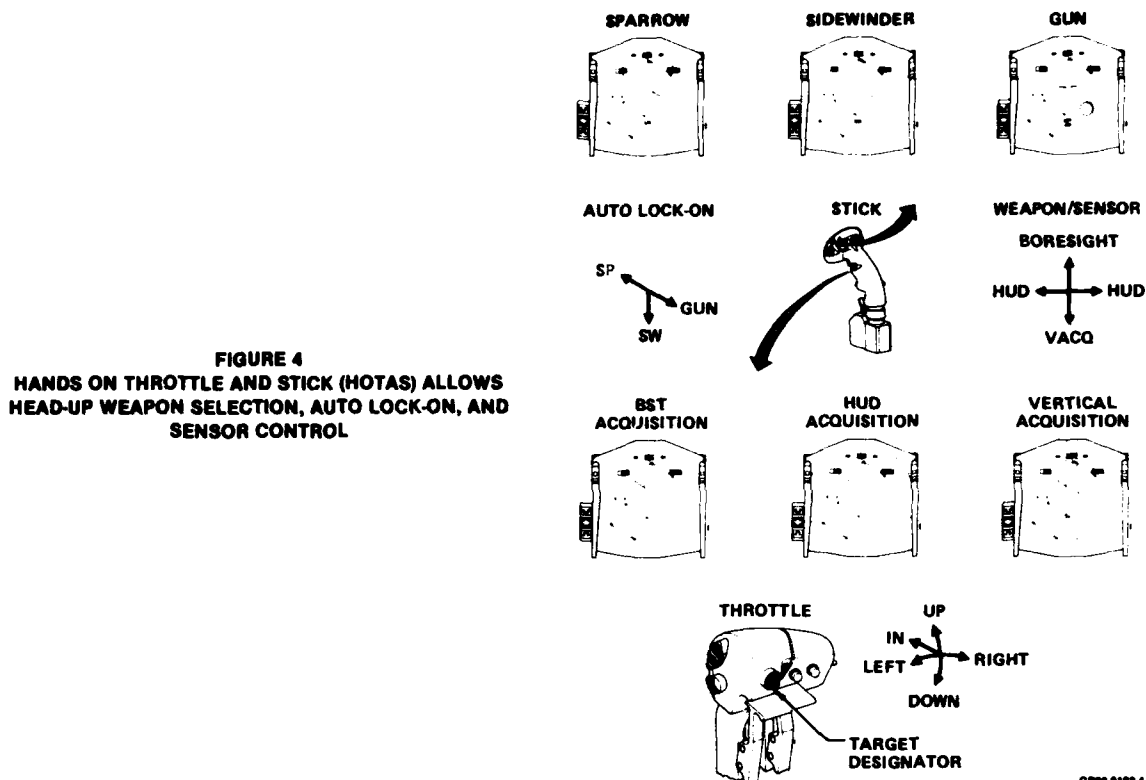
The solution to these three problems was to use computer aided controls and displays to minimize vertigo and error-including console activity by: 1) Weapon and sensor management via a hands-on-throttle-and-stick (HOTAS) concept; 2) CNI management via the up-front control (UFC) immediately in front of the pilot; 3) Master Monitor Moding via the switches surrounding the three head-down CRT displays.

HANDS ON THE THROTTLE & STICK (HOTAS)

The HOTAS concept utilizes switches on the stick and throttle (Figure 4) to allow the pilot to control the weapon, sensors, and displays during time critical portions of the attack while maintaining full control of the aircraft. Although at first glance the number of switches might appear to be complex and confusing to operate, MCAIR simulation and flight experience using fleet pilots indicates they are easily learned because the constant availability of the switches under the pilots' fingers encourages practice and there is always a specific visual feedback of each selection on one or more of the displays. Thus an incorrect selection can be corrected in fractions of a second.

The three primary HOTAS switches are the Weapon Selector and Auto Lock-On selector on the stick, and the Target Designator on the throttle. Weapon selection automatically conditions the radar to nominal parameters for range, azimuth, elevation and Pulse Repetition Frequency (PRF) for Sparrow, Sidewinder, or Gun search. In effect, this allows the pilot to conveniently vary the radar search pattern with his right thumb. The HUD, MFD, and MMD each display sufficient portions of those parameters for the pilot to verify his selection immediately. The three Position Automatic Lock-On switch on the stick is used for visual lock-on and offers a 3° boresight circle on the HUD for pinpoint fly-to lock-on, a 20° circle on the HUD for fast search/acquisition within the HUD field-of-view, and a vertical scan racetrack symbol opening off the top of the HUD for off-boresight lock-on whereby the pilot rolls the aircraft until the target is centered above the rear-view mirror on the canopy bow. Lock-on is automatic in all modes and is conveyed symbolically to the pilot on the HUD and MFD and via a "LOCK" light on the canopy bow.

The Target Designator Control (TDC) on the throttle is a force controlled switch which moves the appropriate designator symbol on the displays in any direction. Computer and sensor designation is accomplished by pressing and releasing the TDC switch. The small cockpit space available and the easily learned use of the TDC prompted some early simulator experimentation with TDC control of essentially all radar control panel functions. In a nutshell, when the pilot wishes to change radar, azimuth, mode, bar scan, or any of the numerous selections normally available on a dedicated radar panel he simply slews the MFD TDC symbol over the displayed quantity he wishes to change and cycles the TDC button until the desired quantity appears. After a little practice, fleet pilots have demonstrated the capability of changing a radar parameter in less than a second elapsed time without removing their hand from the throttle. This feature not only increases pilot effectiveness but also deletes a complex radar control panel and, because of the display redundancy, actually increases the reliability of the function.

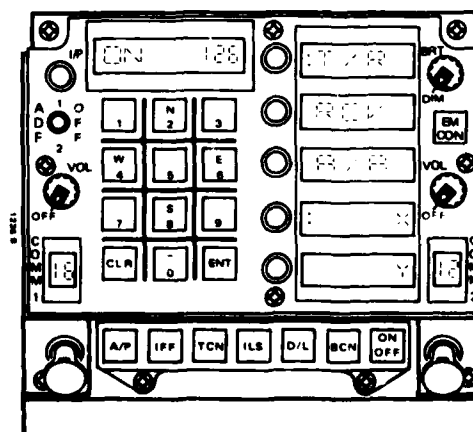


The HOTAS concept allows the pilot to perform a complete head-up, sensor aided gun or missile attack from detection through weapon delivery without removing his hands from the stick or throttle. Similar HOTAS functions are performed for air-to-surface weapon delivery and the pilot need only select Sparrow, Sidewinder, or Gun to revert to air-to-air when coming off the target.

CNI MANAGEMENT

The Up Front Control (UFC) panel (Figure 5) allows head-up, either hand control of two UHF/VHF radios, ILS, Data Link, TACAN, Beacon, ADF, or auto pilot modes. The panel is mounted on the front face of the HUD within easy reach and view of the pilot. The bottom row of switches select functions and the upper area is composed of a keyboard and scratch pad readout, and five option windows on the right side with associated select buttons. For the example shown, the pilot has selected a TACAN function with channel 125 entered in the keyboard scratchpad and the five TACAN modes are shown in the option windows for pilot selection as desired. After the "enter" button is depressed, all data is entered and the UFC clears. The status of any system or channel frequency is available by simply pressing the appropriate function button. The UFC panel is located so near the over-nose vision line that the pilot can easily perform numerous CNI functions during IFR conditions in formation flight.

FIGURE 5
UP FRONT CONTROL OF RADIOS, ILS, DATA LINK, BEACON, IFF, TACAN, AND ALL NUMERIC ENTRIES CAN BE ACCOMPLISHED WITH EITHER HAND WHILE THE HEAD IS LOOKING FORWARD



MODING

Each of the multifunction displays have 20 push-button switches around their periphery. The display (Figure 6) is formatted such that when sensor data is called up, a quarter inch strip of the perimeter of the CRT is available for display of the primary controls for that sensor. The example shown allows pilot selection of wide or narrow field-of-view, positive or negative picture format, freeze, snowplow, a pitch ladder, and other functions important to the effective use of that sensor without diverting the pilot's attention from the sensor. The primary controls and displays extend from the instrument panel about four inches but still outside of the ejection envelope to allow the pilot to reach them without unlocking or straining against the shoulder harness (Figure 7).

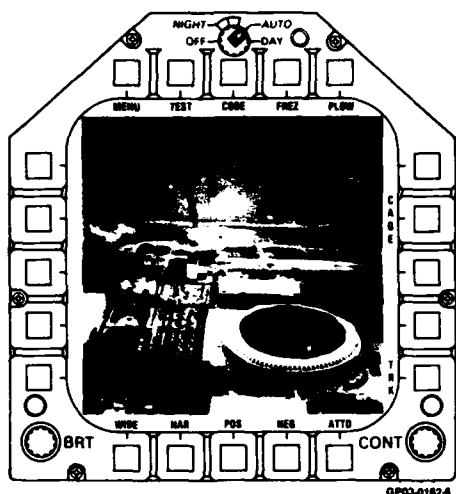


FIGURE 6
THE THREE CRT DISPLAYS EACH HAVE 20 SWITCHES
AROUND THEIR PERIPHERY TO ALLOW PILOT
SELECTION OF RELATED SENSOR FUNCTIONS
WITHOUT DIVERTING ATTENTION FROM THE SENSOR



FIGURE 7
F/A-18 HORNET COCKPIT

MEAGER CONSOLE ACTIVITY

The HOTAS concept, UFC, and display Moding techniques essentially eliminate console activity except for infrequent, low priority items such as instrument lighting, temperature control, some sensor ON/OFF and NAV alignment functions all of which are not time critical, thus significantly reducing the chance of pilot error and vertigo.

SIMULATOR VERIFIED

The simulator program began long before the award of the F/A-18 contract to McDonnell Douglas to verify the HOTAS, Up-Front, and Moding concepts to ensure credibility of the proposed approach.

The present simulator configuration represents the full-up aircraft weapon system with all the controls and displays operational. It is housed in a 40 foot diameter dome on which out-the-window graphics are displayed for air-to-ground, air-to-air, and carrier landing. This simulator, in conjunction with one or two other domes, is used for one-on-one and two-on-one air combat engagements.

In addition to continuous refinement of the one-man-operability techniques by MCAIR pilots, a seven member system advisory panel consisting of fleet pilots from the Navy and Marine fighter and attack community fly the simulator for periods up to one week, numerous times a year to verify that fleet operational doctrine and experience are brought to bear on the design as early as possible. These simulations are fully instrumented and provide a statistical and qualitative figure of merit for alternate approaches to one-man-operability concepts.

The final phases of the simulator program included the installation of the actual aircraft hardware into the simulator for integration and closed loop dynamic operation by MCAIR and fleet pilots prior to the initiation of flight testing.

FLIGHT TESTING

The Hornet full scale development program consists of nine single place and two trainer (two place) aircraft. The first Hornet flight took place at the McDonnell facility in St. Louis on November 18, 1978 with Chief Test Pilot Jack Krings at the controls, and since that time the Flight Test Program has been progressing steadily at Patuxent River Maryland, and Point Mugu California presently accumulating over 4,000 hours flight time. It is the general consensus of the MCAIR and Navy Marine pilots that the display concept and weapon system is indeed versatile, reliable, and one-man-operable. The flight test program will continue through mid-1982 at which time fleet introduction will begin.

BIG R, EASY M

The new look in the U.S. Navy calls for reliability improvements of three to five times those currently experienced in the fleet, and maintenance levels of one-half those of present carrier aircraft. The meeting of this requirement was pursued in a variety of ways:

1. R, M, and cost were considered equivalent to performance and weight in all design decisions.
2. R & M requirement guarantees (not goals) imposed on MCAIR and subcontractors.
3. Incentives were available to MCAIR and selected subcontractors for exceeding the R & M requirement.
4. A stringent parts screening program, derating requirements, and detailed reliability design guidelines was implemented.
5. Early hardware reliability development, test, analyze, and fix required on all major systems giving a two year jump on most past reliability programs.
6. Realistic aircraft operational mission environments were imposed during design and development tests on key systems.

Mission reliability is further enhanced by the display and computer redundancy. Life cycle costs are reduced by common display modules and test programs. The readiness of the weapon system is continually monitored by built-in-test providing 98% failure detection and 99% failure isolation. The MMD in the cockpit presents suitable failure indications to the pilot for easy degraded mode assessment and a Maintenance Monitor Panel in the wheelwell indicates the failed unit to be replaced by the maintenance personnel.

FLEXIBILITY

Long term flexibility is built into the F/A-18. All essential systems and their parameters are available on the multiplex bus, each of the computers and displays have memory and time growth capacity, and the display formats are programmable. This flexibility provides growth for new systems, weapons, and missions. Examples of easily assimilated systems include a new EW suite, modern data transmission methods (JTIDS), and recce/sensor controls and displays. Of immediate benefit to the F/A-18 Hornet is that quick modifications were accomplished during development flight testing by this built-in weapon system flexibility.

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