BEHAVIORAL ENGINEERING LABORATORY
Department of Psychology
New Mexico State University

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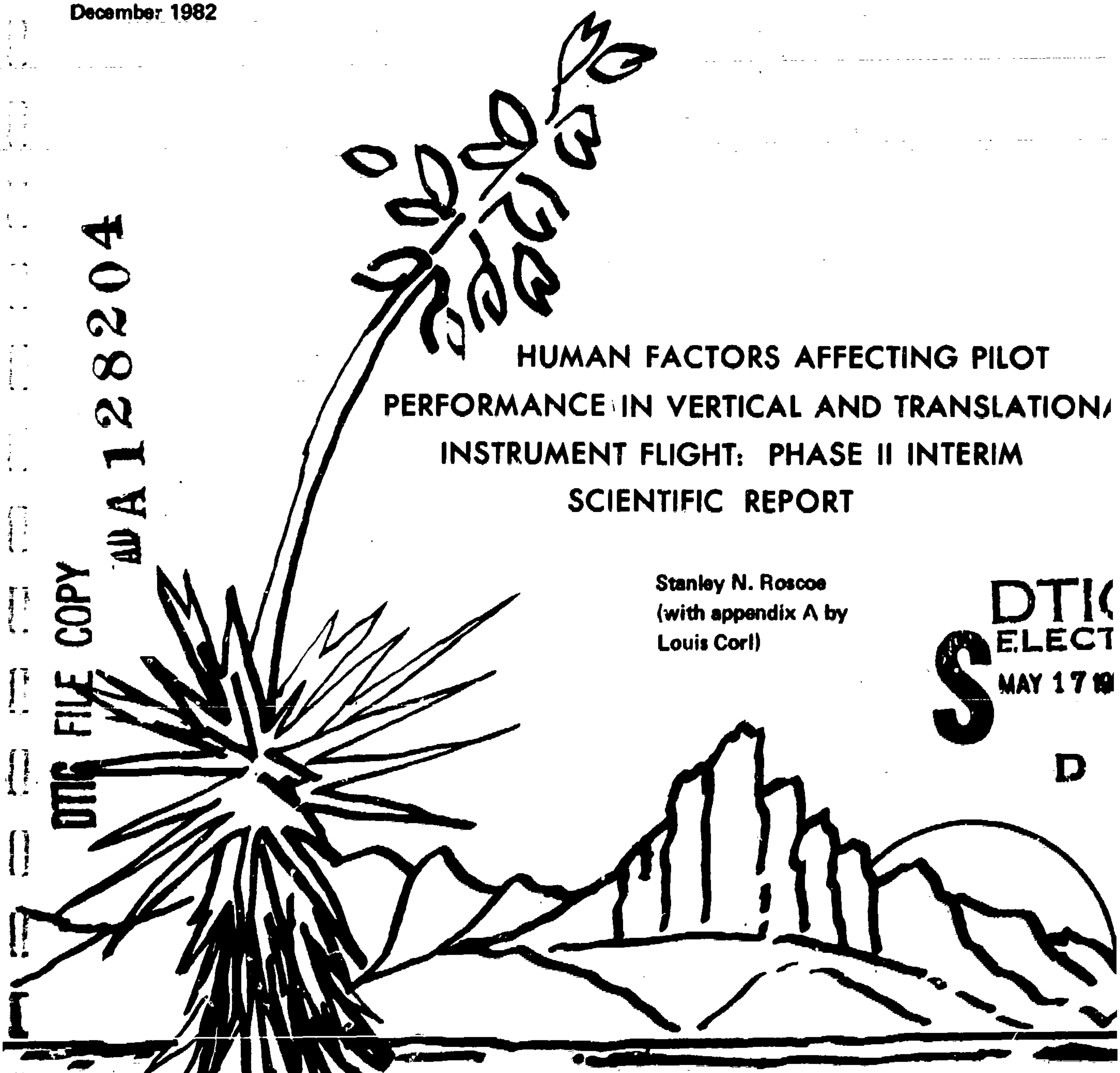

HUMAN FACTORS AFFECTING PILOT PERFORMANCE IN VERTICAL AND TRANSLATIONAL INSTRUMENT FLIGHT: PHASE II INTERIM SCIENTIFIC REPORT

Stanley N. Roscoe
(with appendix A by
Louis Corl)

SUPPORTED BY
ENGINEERING PSYCHOLOGY PROGRAMS
OFFICE OF NAVAL RESEARCH

BEHAVIORAL ENGINEERING LABORATORY

Department of Psychology
Box 5095/Las Cruces, New Mexico 88003
Telephone (505) 646-4716

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A conceptual analysis and review of human factors problems in piloting VTOL aircraft including helicopters is presented. VTOL mission and flight requirements are contrasted with those of CTOLs. Deficiencies in present VTOL flight instrumentation are summarized. An experimental approach that is based on established display principles and emphasizes dynamically predictive skeletal, perspective, vertical and horizontal situation displays is presented.

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Airmass-referenced position
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TABLE OF CONTENTS

BACKGROUND

With the explosion in low-cost, light-weight, and highly reliable computing and display technology, good old display ideas that were once impractical can now be dusted off and implemented. Highly imaginative ideas for orientation, flight control, and navigation displays during the 1940s, 50s, and 60s were spawned under (1) the US Navy Special Devices Center's long standing contract with the University of Illinois (from 1946 until 1966), (2) the Army-Navy Instrumentation Program (ANIP) followed by the Joint Army-Navy Aircraft Instrumentation Research (JANAIR) program, and (3) the US Air Forces's MA-1/F-106 and ASG-18/YF-12 weapon system development programs at Hughes Aircraft Company.

Central innovators in these programs were the late Alexander C. Williams, Jr. of the University of Illinois and Hughes Aircraft; now retired Navy Commander George Hoover; Walter L. Carel of General Electric and later Hughes Aircraft Company, also retired; Henry P Birmingham, now retired, and the late Francis V. Taylor, both of the US Naval Research Laboratory; Charles R. Kelly, formerly of Dunlap and Associates and now in private practice; Carroll T. White of the US Naval Electronics Laboratory, retired; Lawrence J. Fogel, formerly of the Convair Division of General Dynamics, now of Decision Sciences, Inc.; Lawrence A. Scanlan of Hughes Aircraft; and myself, retired from both Hughes Aircraft and the University of Illinois and now with New Mexico State.

Some good old ideas advanced by these people and others included: map-type horizontal situation displays (Williams and Roscoe, 1949); quickened flight-director displays (Birmingham and Taylor, 1954); the contact analog vertical situation display with a highway in the sky (Carel, 1961); pursuit-type predictor displays (Roscoe, 1957; Kelly, 1961); frequency-separated direction of motion displays (Fogel, 1959; Roscoe, 1968); visually time-compressed displays (White, 1960; Scanlan, 1971); rate-field displays (Majendie, 1960); and vernier deviation indicators (Roscoe, 1967/68).

The list could go on, but these concepts stand out (see Appendix B for selected references to these good old ideas). Although each has found limited application, its full potential has not been realized due to technological limitations. Nevertheless, throughout the 1970s the Office of Naval Research, in anticipation of technological advances, supported research on advanced display concepts at the University of Illinois, and now ONR is supporting a program at New Mexico State to put together all these good old ideas in a systematic way for potential application to helicopters and vectored-thrust vertical takeoff and landing (VTOL) aircraft.

EARLY ROOTS

So, in perspective, this program did not start with the present contract. The continuity of my thinking and experimentation on these problems started in 1946 at the University of Illinois under Contract N6ori-71, Task Order XVI, from the ONR Special Devices Center, Port Washington, Long Island, with Clifford P. Seitz as contract monitor and Alex Williams as principal investigator. I was responsible for the flight by periscope experiments; Thomas A. Payne and I for the map display studies; Beatrice Johnson-Matheny for the air traffic control and whole-body rotation research; and Tom Payne and Dora Jean Doughtery, now Dora Strother, for the first measurement of transfer of landing training from a flight simulator with a dynamic closed-loop visual system to the SNJ airplane. This list also could go on and on, but these projects were the most relevant to our present program.

ONR's support of Task Order XVI continued for 20 years at the University of Illinois under the later direction of Jack A. Adams. Meanwhile Williams and I were at Hughes Aircraft working on map displays, radar displays and controls, and air-to-air attack displays (mainly under Air Force programs) until Williams' death in 1962 and my return to Illinois in 1969. Once again I was immediately supported by ONR and James W. Miller, who was soon replaced by Gerald S. Malecki, our current contract monitor. In my second ONR phase at Illinois, I focused on the development and evaluation of the principles of display frequency separation, flight path guidance and prediction, reduced orders of aircraft performance control, and the isolation of necessary and sufficient visual cues in forward-looking displays.

CONTEXT

Problem and Approach

Our present problem with VTOL airplanes and helicopters is how to take advantage of their ability to fly like hummingbirds in the execution of missions totally beyond the capabilities of fixed-wing airplanes, and to do so in bad weather and at night. Progress toward this objective has been relatively slow, largely because of the traditional view that thrust-borne vertical and translational flight is merely a special case of aerodynamic flight. Consequently, almost by default, flight instrumentation for helicopters and vectored-thrust VTOLs has consisted of adaptations of conventional takeoff and landing (CTOL) aircraft instruments that were only marginally acceptable for their original functions.

Our approach is to view thrust-borne vertical and translational flight as the general case and aerodynamic lift and drag merely as special effects of high velocities in certain configurations. Thus we take it that future mission functions can and will involve some independence of control of all six degrees of maneuvering freedom within whatever limits may be designed into a particular airplane. We further assume that the state of the instrumentation art either allows or soon will allow any physical variable of flight--including positions, rates, accelerations, and electromechanical performance--to be sensed with any degree of precision and reliability required.

Missions and Mission Requirements

Helicopters and VTOL craft are all capable of low-speed flight and vertical takeoffs and landings. However, the inherent differences between these two types of aircraft make them suitable for different missions. Helicopters are more suited to low-speed missions such as nap-of-the-earth, air-sea rescue, and antisubmarine sonar dipping. VTOLs are theoretically capable of performing these missions, but their limited time in thrust-borne flight makes them more suitable for high-speed attack missions. These missions impose additional requirements on VTOLs similar to CTOL requirements. Therefore the mission requirements for VTOLs in high-speed attack missions and for helicopters in low-speed missions must each be given special consideration.

Functional requirements for fighter-attack VTOL missions are unlike those of other fighter-attack missions in that they involve greater independence of flight attitude and motion. Within limits VTOLs can point in one direction while moving in another, particularly at slow speeds, and this capability is of great value in air combat maneuvering and ground attack. Although these missions are normally conducted in fair weather, displays are needed that show the relationships among possible, desired, and actual positions, rates, and accelerations.

Functional requirements for helicopter operations derive mainly from the family of missions that involves rapid transitions from one ground-referenced stationary position to another. Examples include antisubmarine sonar dipping, nap-of-the-earth flight, and air-sea rescue operations. In each case the relationships between earth-referenced and airmass-referenced positions, rates, and accelerations must be controlled, and once again actual, desired, and possible values must be taken into account. The basic functional requirement is to fly directly from one hover point to another with any desired heading regardless of the wind; this cannot be done safely on instruments at present.

Deficiencies in Current Instrumentation

The heart of the instrumentation problems with both VTOLs and helicopters has always been the instabilities inherent in conventional control systems. Any realistic hope of achieving the vertical and translational maneuvering potential of these airplanes must start with the adoption of control systems that provide not only stability but direct maneuvering performance control. The Navy's AV-8B airplane represents a major advance in VTOL stability augmentation, and similar advances are being made in stabilizing helicopter control. The degree of direct maneuvering performance control contemplated here would go well beyond current advances.

As progress is made in stabilizing vertical and translational control systems and thereby unburdening the pilot, the deficiencies of current VTOL and helicopter display systems become both more readily apparent and easily addressed. The biggest shortcoming, in the view of thinking operational people, is the traditional attempt, never wholly successful, to present dynamic information on slowly changing position indicators that force the pilot to differentiate rates and accelerations. Furthermore, such displays are, with a few exceptions such as air-speed and angle-of-attack indicators, space-referenced only and not airmass-referenced, a problem that must be dealt with.

Information Requirements

In the most general sense, it is evident that what is needed both in VTOLs and helicopters are integrated forward-looking and downward-looking presentations of the position, rate, and acceleration of the vehicle relative to the external world in all six dimensions of motion. Furthermore, all of these variables either have to be presented in relation to the airmass (how to do this effectively is difficult to imagine despite a proposal for a "snowstorm" display; Roscoe, Hull, Simon, and Corl, 1981), or the effects of airmass movement and turbulence have to be neutralized by means of inertially referenced control (not difficult to imagine and well within the state of the art). And, of course, the actual values of these variables must be related to their corresponding desired and possible values.

In our experimental program, both variable winds and inertially referenced automatic neutralization of wind effects by the control system have been simulated. The effect from the pilot's point of view is the same as flying in a dead calm. Since he no longer has to cope with wind effects in any direct way, there is no need to display airmass-referenced information; airmass effects are sensed and acted on directly by the control system and much faster than is humanly possible.

APPROACH

As Williams (1980, p. 35) summarized his 1947 analysis of the pilot's job:

> Between the knowledge of what control movements to make and the knowledge of the purpose of a mission lie all the areas of information which together result in the accomplished flight. Since the only course of action open to a pilot is through manipulation of the aircraft's controls, it follows that all the information he receives must eventually be filtered down to this level in order for him to participate in the flight at all. These pieces of information somehow work together in an organized way and, for purposes of analysis, must be fitted into some descriptive pattern. . . . Thus, the first problem is to break away from the notion of specific ways for presenting information; the second, to try to develop a scheme into which all pieces of information will fit in a logical way.

Following the master's advice, our approach has been to break away from conventional control and display relationships, arrangements, formats, symbologies, and other sacred cows. These have been replaced by the assumption that the state of the instrumentation art can provide indices of any physical variable of flight with any degree of precision and reliability called for. Furthermore, we view thrust-borne vertical and translational flight as the general case and aerodynamic lift and drag merely as augmentation and/or constraints imposed on otherwise free inertial motion. Thus, mission functions can and will involve, within specific airplane design limits, far greater independence of control in all six degrees of maneuvering freedom.

Given these liberating new degrees of experimental freedom, we have undertaken a systematic reorganization of the control of thrust-borne vehicles and the flow and transfer of information within and between the airplane and pilot. A generic thrust-borne moving body (airplane) is being simulated on the Behavioral Engineering Laboratory's versatile MicroGraphic Simulator. Subject to the resistance imposed by aerodynamic drag, and lift if desired, the vehicle will accelerate along or about any of its axes with the "vectored" application of thrust in accordance with whatever performance capabilities are called for in any specified experimental configuration.

Just as different "airplanes" can be created on call, so can various selectable sets of information and display configurations. To study the effects of alternative divisions of decision and control functions between the pilot and computer, any given subset of information variables can be delivered to either or both. As Williams advised almost 35 years ago, our objective is "to develop a scheme into which all pieces of information will fit in a logical way" so that pilots can fly any thrust-borne mission with information presented in accordance with generalizable principles rather than unique inventions.

Our analytical approach to the implementation of the identified functional and informational mission requirements draws on the basic literature of aviation psychology. Among the best-established applicable display principles are frequency separation and flight-path prediction. The practical embodiment of these complementary principles is achieved by using inertially sensed motion rates and accelerations to present directionally compatible fast-time projections of imminent position in the context of an aircraft-referenced view of relevant objects in the outside world, as well as indices of desired and possible performance.

Our experimental approach to the implementation of realistic requirements involves the systematic manipulation of dynamic and configurational variables in the computer animation of skeletal perspective views of relevant objects and constraints in that same outside world. The basic problem is, and always has been, the fundamental difficulty of unambiguously representing six dimensions of position and attitude (three each) on any practical number of two-dimensional surfaces. We concentrated initially on the forward-looking viewpoint and are now giving attention to the downward-looking view, including basic perceptual questions in the dynamic display of other traffic.

Contact Analog Displays

In configuring a contact analog vertical situation display (VSD), several tradeoffs always have to be made, whether or not the designer is aware of the nature of the alternatives and the consequences of the choices that are eventually selected. The first tradeoff, from which many others stem, is the choice of the physical size of the display itself, or more strictly, the visual angles subtended by the boundaries of the display, whether presented head-up or head-down or as a virtual image generated by a helmet-mounted device that moves with the head.

In any of these cases there is a difficult tradeoff between the desire to present the largest possible outside angular representation (field of view) without increasing display size and without the biased position judgements in ground-referenced flight that result from image compression. This eternal conflict leads to other design tradeoffs that may or may not be considered by the display designer. These include providing selective display magnification (depending on task requirements), displacing the pilot's point of view to a position outside and behind the airplane (presumably a variable distance), and even the possibility of radically unconventional cockpit configurations, each of which was discussed in greater detail in our Phase I Interim Scientific Report (Roscoe et al., 1981).

Cockpit configuration. Briefly reviewing these tradeoffs in the reverse order, we do not find it unreasonable to assume that within this decade sensor and display technology will support ground-referenced flight operations without any direct outside visibility. To make this possible it will be necessary, first, to develop a scanning or other imaging sensor with sufficient cloud-penetrating capability for use in conjunction with high-resolution IR, TV, and optical image intensifying systems; second, to make expected advances in current flat-panel display technology; and finally, to position the pilot slightly farther back in the airplane so that a faceted arrangement of flat-panel displays can provide whatever outside coverage may be required by the missions of the particular helicopter or VTOL craft (see Figure 1).

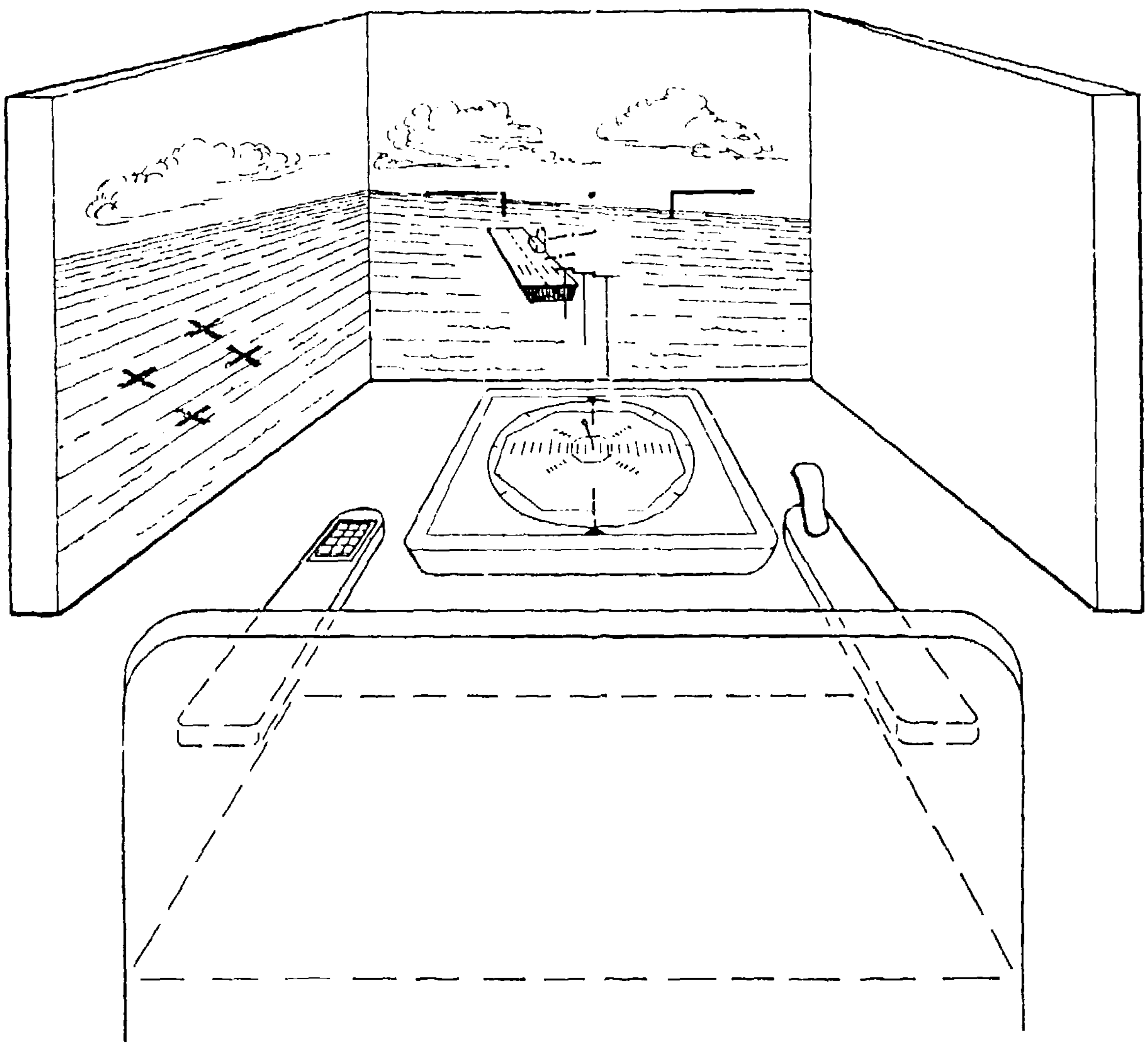

Figure 1. Configuration of cockpit displays and controls for our current ONR program (advanced facility would include third large display at right).

On these display facets surrounding the pilot can be superposed both the sensor-generated imagery and the computer-generated contact analog with its imbedded command guidance and flight path prediction symbology, all beyond the wildest dreams of the early proponents of these original ANIP concepts. Ironically, what may be given up is any direct view of the outside world, which George Hoover considered the ultimate flight display. However, the proposed applications are intended to support zero-visibility ground-referenced flight operations that are currently impossible, and realistically, if pilots are to perform them effectively and safely when the weather is bad, they need to perform them routinely in the same way when it is good.

<u>Displaced viewpoint</u>. In the immediately preceding discussion it was implicit, for the purpose of exposition, that the center of a partial spherical arrangement of display facets is the pilot's head. Furthermore, it was implicit that the sensor- and computer-generated images bear a point-to-point radial correspondence to the picture-plane projections of their outside-world counterparts (when they exist). Though probably desirable, neither of these conditions is necessarily the case, and each is potentially subject to tradeoff compromises. As mentioned earlier, it would be possible, at least in the case of the computer-generated symbology, to displace the pilot's point of view to a position some variable distance behind (or above) the airplane.

While this may seem a strange thing to do, some of its consequences might be advantageous in helicopter control. One such concept has been advanced by CDR Kent Hull of ONR (personal communication). Displacing the pilot's vantage point abaft the helicopter has the effect of including more of the outside world above, below, and to either side of the helicopter within a forward-looking display. Computer-generated symbology can indicate the downward projection of the helicopter's position onto the land or sea surface below, as well as its desired ground track ahead and its projected flight path predicted from current movement and control inputs. By displacing the pilot's vantage point in this way, a single display can serve some of the functions of a downward-looking display as well as those of a forward-looking display.

<u>Display magnification</u>. Imaging displays, whether uncollimated real images or collimated virtual images, cause systematic misjudgments of size, distance, and even angular location of outside objects, the magnitudes of which depend on the individual pilot's dark focus or resting accommodation distance (Roscoe, 1982). Magnifying such displays can compensate for the biased judgements of size and distance but at the expense of no longer maintaining a point-to-point correspondence to the picture-plane projections of counterpart real objects in the outside world. The effectiveness of simply increasing the size of the individual referent objects animated by the computer (as is done with the modeled aircraft carrier in the carrier-landing simulator at Kingsville NAS or with the FLOLS for a different reason in the VTRS at NTEC) may solve the problem.

The Horizontal Situation Display

A wide-angle contact analog display with embedded guidance and prediction symbology serves all mission functions involving spatial and topographical orientation in translational flight, including air combat maneuvering and ground attack. With an optional displaced vantage point, the contact analog can also serve some mission functions involving geographic orientation, including terminal area navigation and short-range en route navigation. However, it cannot be expected to serve all functions equally well, and there are some functions that it cannot serve in even a minimally acceptable manner. Specifically, we cannot expect a contact analog to serve alone in the performance of maneuvers that are very difficult or impossible to perform with contact visibility.

Obvious examples of functions not adequately supported by contact visibility are long-range (beyond line-of-sight) navigation over water and even short-range navigation over water when no surface objects are visible and no shore objects of known location can be identified. Although computer guidance is readily embedded in a contact analog, it is not evident how a pilot would set a desired flight path or navigation plan into a computer by reference to this type of display, and because of its line-of-sight range, the planning function itself is not well supported. Clearly a map-type horizontal situation display (HSD) is needed no matter how capable the VSD.

Collision avoidance. Also, despite the pilot's legal requirement to "see and avoid" other traffic in clear weather, this doctrine is not realistic. Both the detection of other traffic and the extrapolation of potentially conflicting flight paths for collision avoidance require instrumental means. Currently there is an urgent program to implement the cockpit display of traffic information (CDTI). Practical limitations on the fields of view of vertical situation displays prohibit omnidirectional coverage, and for this and other reasons it is properly assumed that CDTI will be embedded in a horizontal display with altitude coding. However, human perceptual ability to extrapolate potential conflicting flight paths is not well understood and needs study.

Transitional control. Less obvious perhaps is the fact that helicopter and VTOL operations at very low speeds near the surface are extremely difficult and hazardous even with the best of visibility, particularly if they require precise horizontal positioning. Sonar dipping, landing on small decks in rough seas, and the transitions between thrust-borne and aerodynamic flight present serious training and safety problems. Since these maneuvers are difficult in clear daylight and currently impossible under instrument meteorological conditions, we cannot expect them to be performed easily and safely solely by reference to a contact analog, even one with guidance and prediction features.

Little attention had been given to the analysis of why these ground-referenced maneuvers are so difficult except to point out the obvious fact that conventional helicopters and VTOLs are terribly unstable in thrust-borne flight. Occasionally it is noted that maintaining position is difficult because it is difficult to detect and judge drift visually and translational rate and acceleration information is not displayed. Nowhere have I found an explicit statement that the focus of difficulty has shifted from the precise control of vertical situation variables (in high-speed translational flight) to the precise control of horizontal situation variables (in vertical flight).

Maneuvering control. Clearly stability and control augmentation are needed in these vehicles, but even with stable rate control of inertial position (fully compensated for airmass movement) an effective presentation of precise horizontal position, rates, and accelerations is needed for maneuvering control. Although map-type HSDs are used in ASW helicopters, they are designed primarily for tactical coordination and not for precise aircraft translational control and station keeping by the pilot. A very large scale HSD showing horizontal and vertical rates and accelerations as well as position and vertical clearance should be more effective than any type of VSD for precise station capture and keeping.

In aerodynamic translational flight VSDs allow precise steering control in the up-down and left-right directions, but they offer little help in controlling forward rates and accelerations. As a consequence we have dedicated airspeed indicators. So in thrust-borne vertical flight, in which precise steering is required in the fore-aft and left-right rather than the up-down and left-right directions, a downward-looking display, or plan view, is needed. The advantage of a special HSD mode for steering control in vertical flight becomes evident once this alternative is considered; what is surprising is that it was not proposed and implemented long ago.

Horizontal Displays for Vertical Flight

For precise translational control and position keeping in vertical flight, a horizontal situation display must present rate and acceleration indications not normally associated with map displays. In effect it becomes a flight control display rather than a navigation display. For this purpose a number of tried and true display principles and techniques can be applied effectively, including frequency separation and vernier deviation indication, as well as command guidance and flight path prediction, mentioned earlier. Also, to support the level of control precision required, an extremely large scale (small area) not normally associated with map displays is required (Dukes, 1970).

The following example illustrates how these principles might be applied to a horizontal display suitable for hovering and translational control in vertical flight (see Figure 2). Present position is always at the center, and the vehicle's heading is indicated by a rotating compass rose read against the fixed index at top center. Translational rates and accelerations along the longitudinal and lateral vehicle axes generate a flight-path predictor emanating from the vehicle's center position. Present altitude is indicated by the size of a hexagon read against a scale emanating laterally from center, and vertical rate by four small rate fields that "flow" in either direction (outward for up, inward for down).

Surface or near-surface objects or positions of tactical relevance are shown relative to the vehicle by variously coded symbology. A target position (goal) is indicated by a small cross (as if painted on the surface) and also by a larger cross that serves as a X10 vernier indication (magnification) of the target's relative displacement from the vehicle. The vehicle's future position predictor is scaled such that when the vernier target cross reaches the head of the predictor symbol, the pilot should reduce his translational rate to maintain the predictor head in the open center of the cross until directly over the goal.

Although this horizontal display is basically an inside-out presentation mapped relative to aircraft heading, motion relationships are compatible with population stereotypes. The second-order flight position predictor is in effect a frequency-separated index that responds immediately to control inputs in the expected direction. Furthermore, the predictor symbol itself incorporates a rate-field indication in the direction of flight, and the flow of the vertical rate indicators constricts as the craft descends to a touchdown and dilates as it ascends. When the numerous dynamic variables have been experimentally optimized, this display should allow precise vertical and translational control in thrust-borne instrument flight.

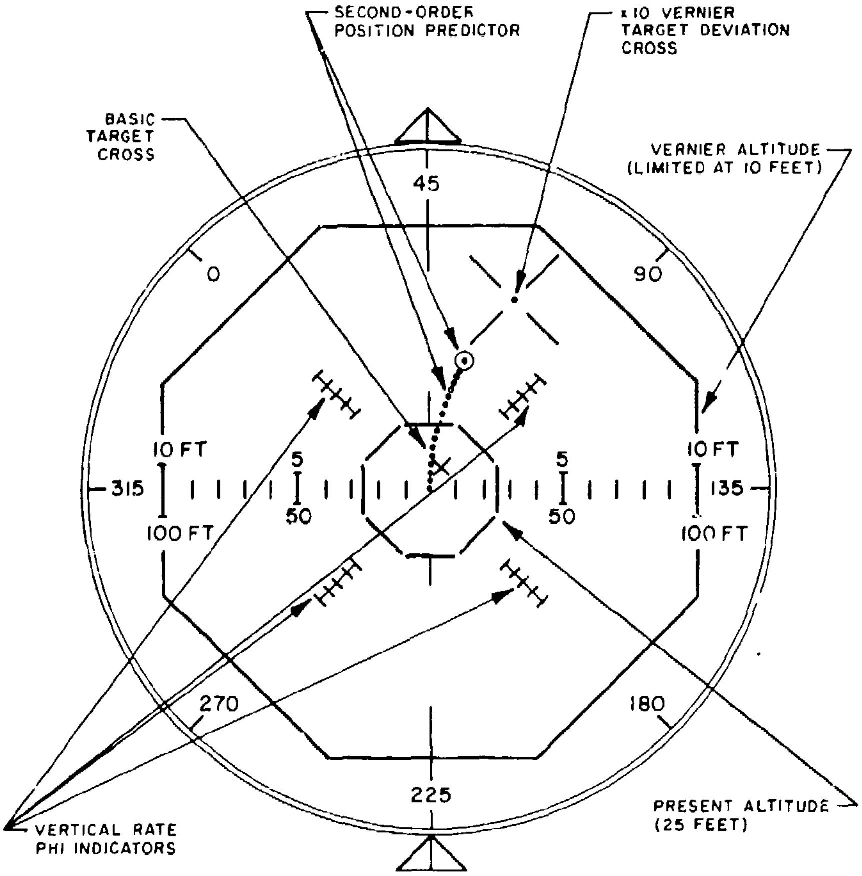

Figure 2. Horizontal display for vertical and transitional flight control.

EXPERIMENTATION

The experimental optimization of the forward (and sideward) pictorial views and the pictographic downward-looking display involves measurement of the precision and stability of manual control of predefined vertical and translational flight maneuvers. The maneuvers are representative of those required in typical VTOL and helicopter missions and include hovering, transitions between vertical and translational flight (point-to-point transitions), and tracking of variable forcing functions as in nap-of-the-earth navigation, terrain following, ground attack, and air combat maneuvering. As an inferential measure of workload, residual attention side tasks are introduced at times.

Experimental variables, in addition to task variables, include:

Display Configuration Variables

1. Size in terms of angular fields of forward and sideward view ranging up to 60 degrees vertically and 120 degrees horizontally (30 degrees right to 90 degrees left).

2. Image magnification of pictorial elements from the reference eye position, variable from X1.0 to X1.5.

3. Displaced eye position (point of view) directly behind and/or above reference eye position by amounts ranging out to 1000 feet or more with X1.0 magnification.

4. Various shapes and sizes of symbols representing critical objects and features viewed from the cockpit such as aircraft carriers, air-capable ships, airport runways and helipads, targets, navigation waypoints, desired flight path (highway-in-the-sky), flight path predictors, and performance envelope limits.

Display Dynamics Variables

1. Order of prediction in each of the six degrees of motion freedom.

2. Ratios of 1st, 2nd, and possibly 3rd orders of prediction.

3. Prediction time constants or scaling coefficients for various mission-related maneuvers.

4. Ratios of application of prediction to own aircraft versus target positions.

Control Dynamics Variables

1. Orders of control in each of the six degrees of motion freedom.

2. Ratios of 3rd, 2nd, and 1st orders of control.

Experimental Strategy

To investigate all these system variables in anything like an efficient way, an holistic approach is necessary. This entails the manipulation of as many independent variables as practical (possibly all of those listed) in a screening experiment to identify critical variables. Thereafter additional information is collected as needed to develop a multiple-regression prediction model that fits all the data well. Whatever their number, if critical variables are held constant in an experiment, unless the fixed values are close to those found in the real world, findings can be grossly inaccurate when applied to operational situations.

EXPERIMENTAL FACILITIES

The Behavioral Engineering Laboratory's versatile PDP-11/23-based MicroGraphic Simulation System originally included a secondary ADAC System 1000 computer, a Hewlett-Packard 1350A Graphics Translator and 1311A Display, and two 512 x 512 dot-matrix plasma-panel displays. This system could be used either with a Frasca helicopter simulator or in conjunction with the generic control-configured VTOL vehicle simulation described previously (also see Appendix A of our Phase I Interim Scientific Report). The operator can be presented with forward-looking and/or downward-looking displays.

From the outset of this program we were thinking of a vertical situation display far larger than our 8-1/2 X 11-inch Hewlett-Packard CRT screen. However, during the first phase of our study, I visited several consultants with helicopter operational and flight test experience. Also I visited Cherry Point Naval Air Station and talked with Marine Harrier VTOL instructors and students. As I asked questions and listened, it became increasingly clear that field-of-view requirements were even greater than I had imagined. Small field of view is the number one problem with the imaging displays used in helicopters, and limited forward visibility in contact flight is the second thing mentioned by Harrier pilots (after control instability).

I substantially revised my concept of where we should be heading experimentally and where vertical and translational flight displays should be heading operationally. I had been thinking of much larger head-down displays than any to date, but they would not provide the angular coverage I now believe is required without severe and damaging scale minification. The required display size cannot be specified absolutely, but our thinking as reflected in the Phase I Interim Scientific Report places a premium on a cockpit display that fills a very large forward and sideward field of view both laterally and vertically.

Large here means at least 180 degrees side-to-side and 60 degrees top-to-bottom. This could be achieved with a single spherical or cylindrical shell section or with multifaceted flat displays. Clearly these displays would replace other cockpit instruments and even cover windows (although they might be transparent as George Hoover originally imagined). The rationale is that, if pilots are to fly in bad weather or at night using only the displays, they should practice flying with them even when there is something to be seen outside. The challenge is also clearly there to provide better information on the displays than can be seen out the windows when visibility is excellent.

To implement our expanded research objectives, we have expanded our experimental facilities by the addition of two large (17 X 17-inch) transparent plasma display screens to replace our Hewlett-Packard CRT. One will present a 60 X 60-degree view directly forward and the second a similar view from 30 to 90 degrees to the left of straight ahead. Our downward-looking horizontal display can be presented either on an 8-1/2-inch-square plasma screen or on the Hewlett-Packard CRT display.

The expanded facility will be in operation early in 1983, thereby leaving more than a year for experimentation during the remainer of the contractual period. Meanwhile we are currently conducting experiments to optimize the horizontal display, and one experiment has been completed on the human ability to extrapolate the tracks of other traffic presented dynamically on a horizontal cockpit display. We have made advance plans to transfer our resulting optimized display configurations (and the computer programs that generate them) to the Naval Ai Test Center for operational test and evaluation and to the Visual Technology Research Simulator at the Naval Training Equipment Center to investigate possible training applications.

APPENDIX A: ADVANCED FACILITY CONCEPT

by Louis Corl

Although the facility just described will allow experimental investigation of all display variables previously enumerated, it still presents serious limitations. With serial writing on plasma displays, the number of pixels that can be addressed per frame allows only a few lines to be drawn. As a result only very simple scenes can be created. Furthermore, our single PDP-11/23 computer can practically handle only one display "window" at a time while our subsidiary LSI-11/03 (ADAC System 1000) is dedicated to the 8-1/2-inch square horizontal display.

For several months we have been gathering information and conducting tradeoffs to determine the best practical approach to a research facility that will provide the speed and flexibility to support large multifactor experiments involving all critical display variables simultaneously. The result is an advanced research facility plan. In view of the current revolution in rastergraphic technology, final selection of specific hardware should be delayed as long as possible to take advantage of the most advanced items available at the time of procurement.

Facility Architecture

The facility would consist of:

A. one master computer to simulate the characteristics and flight of the aircraft, transmit the resulting information to the three vertical display computers (and to the horizontal display directly), and collect and reduce pilot performance data,

B. three display computers, each dedicated to one display,

C. three bit-map controllers, similarly dedicated to individual displays,

D. three large display screens (17 X 17-inch plasma panels) with 1024 X 1024-pixel resolution and 1024-line parallel address interfaces,

E. three optical projection systems with rear projection screens (to provide the display magnification of about X1.5 and thereby eliminate blind sectors between display "windows"), and

F. a flight seat with variable characteristic armrest-mounted manual flight controls as well as any keyboards or other input devices.

The master computer is run by the experimenter from a standard console. This computer runs the program to schedule the various phases of the mission, collect data from the subject console, and calculate the modeled vehicle's resulting location, attitude, and configuration states. The results of these computations are then transmitted to each of the large displays. The master computer also uses the results to create an appropriate horizontal situation display. Performance data are collected during and reduced at the end of the flight by the master computer.

Each large display contains a computer for receiving location and attitude data from the master computer and for running the program that decides what parts of the modeled world are visible on the particular display. The computer passes information to the bit-map controller regarding what lines and curves are visible on the display, and the bit-map controller turns on the appropriate bits. Then when a complete bit-map has been produced, the plasma panel is refreshed in 20 ms from the bit-map. A projection system for enlarging the 17-inch square plasma panel 1.5 to 1 onto a rear projection screen placed at 22 inches from the subject's eye position completes the large display (see Figure 3).

The master computer is the only one that has floppy disks and a video terminal. Rather than having a console at each computer for each of the large displays, the master computer has a serial link by which it gets the slave started after power-up. A high-speed direct memory access (DMA) controller in each machine allows the master to transfer large amounts of data to each of the display computers. During the running, the master passes to all three display computers information regarding the current view of the world, and each display computer then computes what appears on its display surface.

The master computer must be able to collect quickly from the subject's console all information regarding control inputs. For this purpose a high-speed analog to digital converter is included. It can digitize 16 controlled variables in 160 microseconds. Digital input from keyboards or switches can be input rapidly through the DMA interface. Once the subject inputs have been collected, the master computer must apply them to the controlled vehicle model. This extensive series of calculations is quite mixed, with the next required calculation equally likely to be an addition, subtraction, multiplication, or division. For this reason the computer needs to be able to achieve high computational speed on a mixed selection of operations. The hardware chosen for this operation is a floating point processor card.

The floating point processor card can achieve a speed improvement of 4.5 for addition and subtraction and 7.0 for multiplication and division over the floating point instruction chip which is part of the central processing unit (CPU) chip set. Without any such floating point hardware (chip or processor card) the time for addition and subtraction is slower by a factor of 1.8 and for multiplication and division it is slower by a factor of 2.7 than the chip. At the speed of the floating point processor an arithmetic operation takes about the same time as the ordinary computer instructions of which the rest of the program is composed.

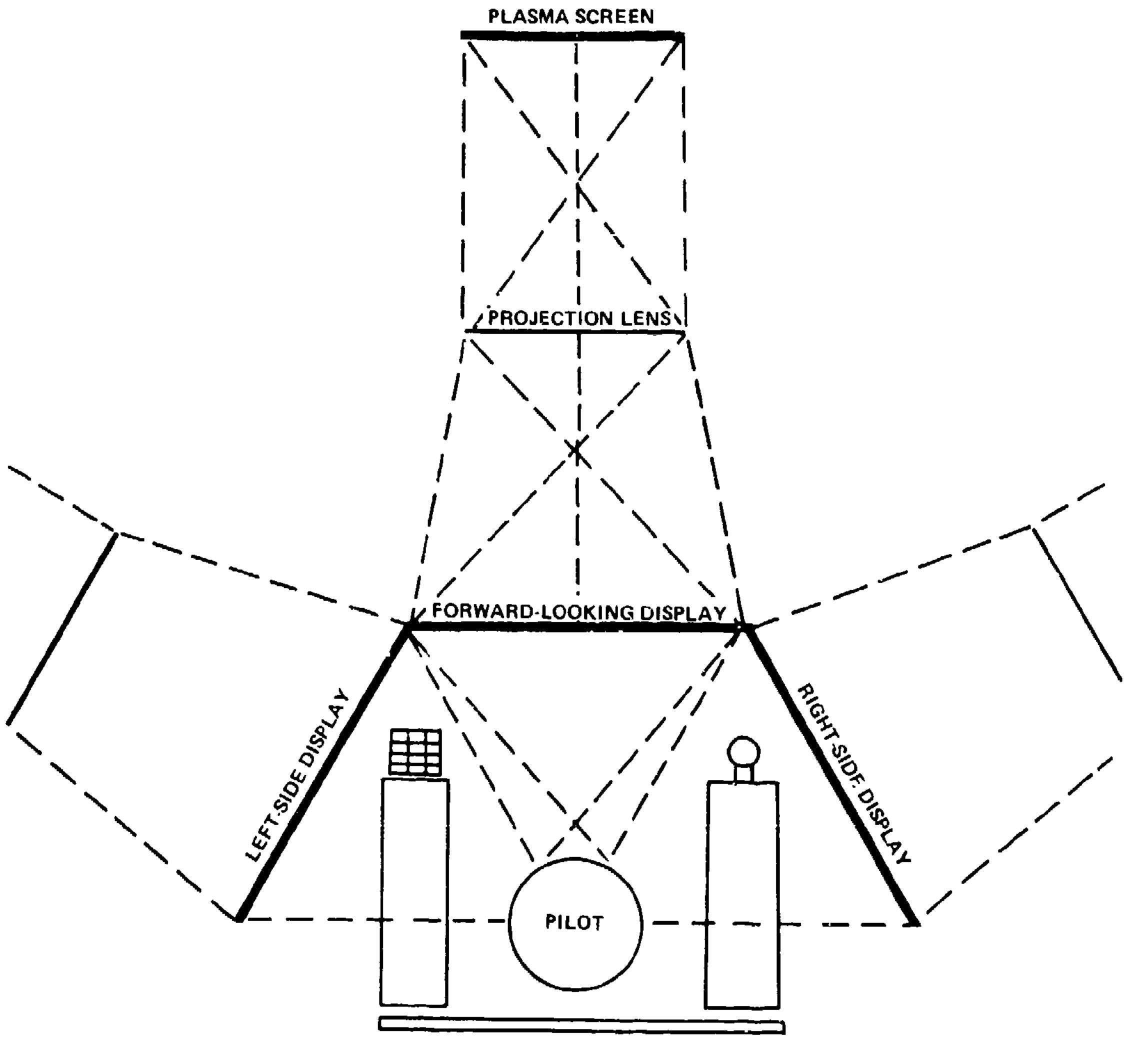

Figure 3. Arrangement of displays and controls.

The result of computation of the modeled vehicle is the position and attitude of the vehicle in the modeled world. This information is all that is required to determine what parts of the modeled world are visible on each of the displays. First, however, each large-display computer must use the position and attitude data to transform all the world points into subject viewing coordinates. This operation is a repetitive process using a few constants for all the world point x, y, and z numbers. For this kind of computation an array processor will be much faster than the floating point processor.

The array processor requires some setup time to get things going, but once it is computing at full speed it can turn out a product or sum of two numbers in about 1 microsecond. This is at least 10 times faster than the floating point processor. Points in the world can be transformed to points in the subject's viewing system at the rate of 50 in 1 ms, so that a world with 600 lines (at most 1200 endpoints) would require less than 24 ms of computation.

Once the subject viewing coordinates have been computed, each large-display computer must begin deciding which of the 600 lines in the world example above are visible in its field of view and clipping to its screen edge any which leave. Again, this sort of computation requires the speed of a floating point processor but is not structured for the array processor to provide a benefit. The information concerning on-screen lines is passed to the bit-map controller by way of a second DMA interface in the large-display computer.

The master computer also has information from the model concerning velocities and accelerations from which to make predictions of future values of position and attitude. It has a plan of the mission with which to create desired position and attitude information. It also contains the current values of vehicle variables such as airspeed or engine operating parameters. This information must be provided to each of the large-display computers to allow it to generate the appropriate displays of this information. When the large-display computer has finished evaluating all the information, it signals the bit-map controller which initiates a plasma panel rewrite cycle to transfer the completed bit-map onto the display.

APPENDIX B: SELECTED REFERENCES TO GOOD OLD IDEAS

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Arlington, VA 22217

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Office of Naval Research
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Arlington, VA 22217

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Naval Medical R&D Command
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Naval Medical Center
Bethesda, MD 20014

Dr. George Moeller
Human Factors Engineering Branch
Submarine Medical Research Lab
Naval Submarine Base
Groton, CT 06340

Head
Aerospace Psychology Department
Code L5
Naval Aerospace Medical Research Lab
Pensacola, FL 32508

Dr. Earl Alluisi
Chief Scientist
AFHRL/CCN
Brooks AFB, TX 78235

Dr. S. Schiflett
Human Factors Section
Systems Engineering Test
Directorate
U.S. Naval Air Test Center
Patuxent River, MD 20670

CDR C. Hutchins
Code 55
Naval Postgraduate School
Monterey, CA 93940

Dr. Edgar M. Johnson
Technical Director
U. S. Army Research Institute
5001 Eisenhower Avenue
Alexandria, VA 22333

Director, Organizations and
System Research Labortory
U.S. Army Research Institute
5001 Eisenhower Avenue
Alexandria, VA 22333

Technical Director
U.S. Army Human Engineering Labs
Aberdeen Proving Ground, MD 21005

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Development Center
Command and Support Systems
San Diego, CA 92152

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Human Factors Engineering Division
Naval Air Development Center
Warminster, PA 18974

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Human Facors Engineering Center
Naval Air Development Center
Warminster, PA 18974

Mr. Jeffrey Grossman
Human Factors Branch
Code 33152
Naval Weapons Center
China Lake, CA 93555

Human Factors Engineering Branch
Code 1226
Pacific Missile Test Center
Point Mugu, CA 93042

Dr. Gary Poock
Operations Research Department
Naval Postgraduate School
Montery, CA 93940

Chief, Systems Engineering Branch
Human Engineering Division
USAF AMRL/HES
Wright-Patterson AFB, OH 45433

Director, Human Factors Wing
Defense & Civil Institute of
Environmental Medicine
Post Office Box 2000
Downsview, Ontario M3M 3B9
Canada

U.S. Air Force Office of Scientific
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Life Sciences Deirctorate, NL
Bolling Air Force Base
Washington, D.C. 20332

Defense Technical Information Center
Cameron Station, Bldg.
Alexandria, VA 22314 (12 cys)

Dr. Craig Fields
Director, System Sciences Office
Defense Advanced Research Projects Agency
1400 Wilson Blvd
Arlington, VA 22209

Dr. William R. Uttal
Operations Research Department
University of Michigan
Ann Arbor, MI 48109

Dr. M. Montemerlo
Human Factors & Simulation Technology, RTE-6
NASA HQS
Washington, D.C. 20546

Dr. Robert R. Mackie
Human Factors Research Division
Canyon Research Group
5775 Dawson Avenue
Goleta, CA 93017

Dr. Robert T. Hennessy
NAS - National Research Council (COHF)
2101 Constitution Ave., N.W.
Washington, D.C. 20418

Dr. Amos Freedy
Perceptronics, Inc.
6271 Variel Avenue
Woodland Hills, CA 91364

Dr. Robert Williges
Dept. of Industrial Engineering & OR
Virginia Polytechnic Institute and State Universtiy
130 Whittemore Hall
Blacksburg, VA 24061

Dr. Robert Fox
Department of Psychology
Vanderbilt University
Nashville, TN 37240

Dr. Charles Gettys
Department of Psychology
University of Oklahoma
455 West Lindsey
Norman, OK 73069

Dr. Jesse Orlansky
Institute for Defense Analyses
1801 N. Beauregard Street
Alexandria, VA 22311

Dr. T. B. Sheridan
Department of Mechanical Engineering
Massachusetts Institute of Technology
Cambridge, MA 02139

Dr. Wayne Zachary
Analytics, Inc.
2500 Maryland Road
Willow Grove, PA 19090

Dr. Harry Snyder
Department of Industrial Engineering
Virginia Polytechnic Institute and State University
Blacksburg, VA 24061

Dr. James H. Howard, Jr.
Department of Psychology
Catholic University
Washington, D.C. 20064

Dr. William Howell
Department of Psychology
Rice University
Houston, TX 77001

Dr. Christopher Wickens
Universtiy of Illinois
Department of Psychology
Urbana, IL 61801

Dr. Edward R. Jones
Chief, Human Factors Engineering
McDonnell-Douglas Astronautics Company
St. Louis Division
Box 516
St. Louis, MO 63166

Dr. Douglas Towne
University of Southern California
Berhavioral Technology Latoratory
3716 S. Hope Street
Los Angeles, CA 90007

Dr. Babur M. Pulat
Department of Industrial Engineering
North Carolina A&T State University
Greensboro, NC 27411

Dr. Joseph G. Wohl
Alphatech, Inc.
3 New England Industrial Park
Burlington, MA 01803

Dr. Stanley N. Roscoe
New Mexico State University
Box 5095
Las Cruces, NM 88003

Human Factors Technology Administrator
Office of Naval Technology
Code MAT 0722
800 N. Quincy Street
Arlington, VA 22217

Mr. Philip Andrews
Naval Sea Systems Command
NAVSEA
Washington, D. C. 20362

Commander
Naval Air Systems Command
Human Factors Programs
NAVAIR 340F
Washington, D. C. 20361

Dr. Lola Lopes
Information Sciences Division
Department of Psychology
University of Wisconsin
Madison, WI

Dr. Richard Pew
Bolt Beranek & Newman, Inc.
50 Moulton Street
Cambridge, MA 02238

Dr. David J. Getty
Bolt Beranek & Newman, Inc.
50 Moulton Street
Cambridge, MA 02238

CDR J. Funaro
Human Factors Engineering Division
Naval Air Development Center
Warminster, PA 18974

Commander, Naval Air Force,
U. S. Pacific Fleet
ATTN: Dr. James McGrath, Code 50A
Naval Air Station, North Island
San Diego, CA 92135