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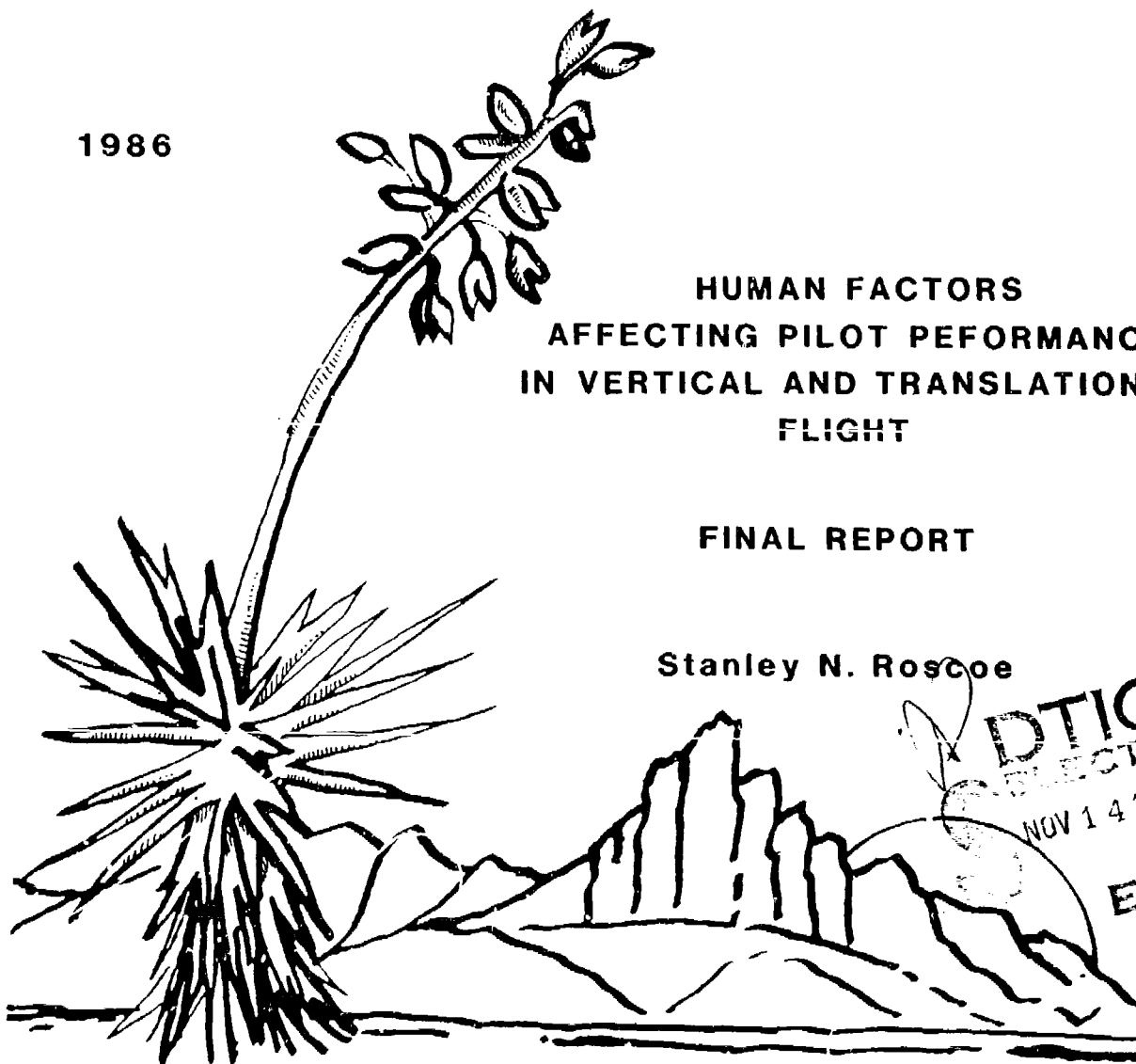Work Unit NR 196-170

1986

HUMAN FACTORS
AFFECTING PILOT PEFORMANCE
IN VERTICAL AND TRANSLATIONAL
FLIGHT

FINAL REPORT

Stanley N. Roscoe

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This report is a review of a program to apply the best aircraft control and display ideas and principles generated since World War II to an integrated, computer-based system for vertical and translational instrument flight. A generic thrust-borne aircraft capable of vertical takeoff and landing (VTOL) and six degrees of maneuvering freedom was simulated, as were a forward-looking contact analog display and a

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downward-looking horizontal situation display. Features incorporated in these displays included command guidance symbology, directionally compatible frequency-separated quasi-pursuit flight path predictors with vernier-deviation indications and uniquely integrated presentations of altitude and vertical speed in the horizontal situation display. Features of the simulated control system included automatic stabilization of position and velocity vector against air mass movements and reduced orders of maneuvering performance control. A holistic experimental approach was applied to screen critical dynamic design variables, optimize their response surfaces, and investigate direction of display motion relationships, all leading to multiple-regression models of pilot performance in vertical and translational instrument flight.

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CONTEXT

Consider the hawk and the hummingbird and by way of analogy the conventional fixed-wing airplane and the various vertical takeoff and landing (VTOL) airplanes including helicopters. Conventional airplanes, like hawks, are supported largely by aerodynamic lift and can soar and glide great distances without movement or propulsive thrust. VTOL airplanes, like hummingbirds, can't soar nor can they glide far, and they depend on propulsive thrust to maintain airborne flight. But hummingbirds and VTOLs are not without advantages, for their degrees of maneuvering freedom far exceed those of hawks and fixed-wing airplanes. (Although helicopters can take off and land vertically, we will use the term VTOL hereafter to refer specifically to aircraft whose vertical flight capability depends on vectored thrust rather than that produced by a rotary wing.)

The 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 hand-me-down adaptations of conventional takeoff and landing (CTOL) aircraft instruments that were only marginally acceptable for their original functions.

The approach advanced in the research program to be reviewed adopts the converse perspective, namely, that thrust-borne flight is the more general case and that aerodynamic lift and drag are merely the special effects of high velocities in certain configurations. It is assumed that future VTOL missions will involve some independence of control in all six degrees of maneuvering freedom within whatever limits may be designed into a particular aircraft. It is further assumed that the state of the instrumentation art either allows or soon will allow any physical variable of flight to be sensed with sufficient resolution, precision, and reliability for its intended use.

Given this point of view and these not unreasonable assumptions, how would one go about capitalizing on the recent explosive advances in computing and display technology to make it possible for pilots to fly VTOLs in bad weather and at night as hummingbirds fly in good weather during the day? Our approach was to attempt a symbiotic integration of all the display and control design principles individually conceived and validated during the 40 years of ergonomic research since the Second World War and to optimize their combination experimentally. (When I use "we" or "our," it is not in the editorial sense; I am referring to my graduate students and associates.)

BACKGROUND

Highly imaginative display and control ideas for spatial orientation, navigation, and flight control were conceived during the 1940s, 50s, and 60s 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 Instrumenta-

tion Program (ANIP) followed by the Joint Army-Navy Aircraft Instrumentation Research (JANAIR) program, and (3) the US Air Force's MA-1/F-106 and ASG-18/YF-12 weapon system development programs at Hughes Aircraft Company.

Some good display and control ideas and design "principles" advanced in those programs included: map-type horizontal situation displays (Williams and Roscoe, 1950; Roscoe et al., 1950; Payne, 1952; Roscoe, 1953, 1954, 1957, 1968a); the contact analog vertical situation display with a highway in the sky (Carel, 1960, 1961); pursuit-type predictor displays (Simon and Roscoe, 1956; Roscoe, 1957; Bauerschmidt and Roscoe, 1960; Kelley, 1960, 1962, 1968); frequency-separated direction of motion displays (Fogel, 1959; Roscoe, 1968b); vernier deviation indicators (Roscoe, 1968a); and reduced orders of control (Roscoe, 1953; Roscoe and Kraus, 1973).

The list could go on, but these concepts stand out. Although each has found limited application, its full potential has not been realized due to technological limitations and emotional resistance. Nevertheless, the US Office of Naval Research, in anticipation of technological advances, supported research on advanced display concepts at the University of Illinois throughout the 1970s and at New Mexico State University in the early 1980s to put together all these ideas and principles in a systematic way for potential application to helicopters and VTOL aircraft.

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 flight, air-sea and mountain-side 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 air combat and high-speed attack missions. These missions impose additional requirements on VTOLs similar to CTOL requirements.

However, functional requirements for fighter-attack VTOL missions are unlike those of CTOL 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 for contact as well as instrument flight operations.

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 rescue operations. In each case relationships between earth-referenced and airmass-referenced positions, rates, and accelerations must be controlled, and 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 (Ringland et al., 1977). 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 (Roscoe and Bergman, 1980). The US 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 and Control Requirements

In the most general sense, it is evident that VTOLs and helicopters need integrated forward-looking and downward-looking presentations of the acceleration, velocity, and position 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 et al., 1981a), 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 almost the same as flying in a dead calm. Because 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.

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.

APPROACH

Following Williams' advice, our approach has been to break away from
conventional control and display relationships, arrangements, formats,
symbologies, and other sacred cows. Given these liberating new degrees of
experimental freedom, we undertook 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 (VTOL
aircraft) was simulated on our versatile MicroGraphic Simulator. Subject to
the resistance imposed by aerodynamic drag, and lift if desired, the simulated
vehicle would 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" could be created on call, so could 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 could be
delivered to either or both. As Williams advised almost 40 years ago, our
objective was "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 drew on the basic literature
of aviation psychology. Among the best-established applicable display
principles are frequency separation and flight-path prediction (Roscoe, 1968b,
1980; Beringer et al., 1975; Ince et al., 1975; Roscoe and Williges, 1975;
Roscoe and Jensen, 1981; Roscoe et al., 1980; Jensen, 1981; Roscoe et al.,
1981b). The practical embodiment of these complementary principles was
achieved by using inertially sensed accelerations and rates 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 performance.

To cope with the historically incompatible needs to present "the big
picture" for geographic orientation and navigation planning and a magnified
view of "the local picture" for precise flight control, the "vernier deviation
indicator" principle was applied. This technique had received little
experimental attention but proved quite effective in an early application
(Roscoe, 1968a). Providing a large-scale error indication relative to present

position on a smaller-scale display is analogous to viewing a small local area of a map through a magnifying glass. Used in conjunction with a fast-time predictor of imminent position, a vernier deviation indication allows precise manual flight control without sacrificing the big picture.

Our experimental approach to the compatible integration of these and other principles involved 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 was, 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 view appropriate to translational flight but soon discovered that it was the downward-looking viewpoint that is most needed and best used in vertical and transitional flight.

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 (Roscoe, 1982a). 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. (Unfortunately, when a new display idea is first implemented, display size is typically an afterthought.)

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 judgments in ground-referenced flight that result from image compression (Roscoe et al., 1966). This eternal conflict leads to other design tradeoffs that may or may not be considered by the display designer. These include providing variable 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 an early report (Roscoe et al., 1981a).

Cockpit configuration. Briefly reviewing these tradeoffs, we did 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 would be necessary, first, to develop an 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 aircraft so that a faceted arrangement of flat-panel displays can provide whatever outside coverage may be required by the various missions.

On these display facets surrounding the pilot would be superposed both the sensor-generated imagery and the computer-animated 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 the ANIP proponents 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.

Displaced viewpoint. 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-generated and computer-animated 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-animated 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 or VTOL control. One such concept was
advanced by CDR Kent Hull of ONR (Roscoe et al., 1981a). Displacing the
pilot's vantage point abaft the aircraft has the effect of including more of
the outside world above, below, and to either side within a forward-looking
display. Computer-animated symbology can indicate the downward projection of
the aircraft'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.

Display magnification. Imaging displays, whether real or virtual, 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 et al., 1966; Randle et al.,
1980; Hull et al., 1982; Roscoe, 1982c, 1984, 1985; Roscoe et al., in press).
Magnifying such displays can compensate for the biased judgments 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
visual systems in some flight simulators) may solve the problem.

Horizontal Situation Displays

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.

Furthermore, 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 under the best of visibility. 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.

Less obvious perhaps is the fact that helicopter and VTOL operations at very low speeds near the surface also 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. Because 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.

Horizontal Displays for Vertical Flight

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 directly. 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 and transitional flight).

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 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 capturing 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 maintaining stable control is more difficult in the fore-aft and left-right directions than it is in the up-down direction, a downward-looking display, or plan view, is needed. The advantage of a special HSD mode for steering control in vertical and transitional flight becomes evident once this alternative is considered; what is surprising is that it was not proposed and implemented long ago.

Because VSDs are primarily associated with precise steering in azimuth and elevation during translational flight, topographic detail is normally limited to such items as airports, carriers, ships with small landing decks, tactical target locations, and possibly surface buoys or radio facilities. In operations over land, terrain elevations may be shown in perspective contours suitable for terrain following or avoidance, and these computer-animated representations may be augmented by sensor imagery revealing the locations of specific objects such as bridges, buildings, tanks (of either kind), or other items of tactical importance.

Map displays, on the other hand, not only present the big picture but can contain a wealth of topographic information limited only by available intelligence and the need to avoid clutter and confusion. Furthermore, map items and other traffic in the vicinity can be identified by various abstract symbols and by specific numerical and verbal identifiers that would be totally impractical with dynamic pictorial vertical situation displays. For many purposes pictures are more effective than abstract symbols, but the converse can also be true; it is far easier to recognize and remember a specific number between 1 and 9 than it is to pick a stickup man out of a police lineup.

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 as well as a navigation display. For this purpose a number of display principles and techniques can be applied effectively, including frequency separation and vernier deviation indication (VDI), as well as command guidance and flight path prediction (Roscoe, 1968a, 1968b, 1980, 1982b; Roscoe et al., 1980). Also, to support the level of control precision required when no flight path command is available (hence no VDI), an extremely large scale (small area) not normally associated with map displays is required (Dukes, 1970).

Simulation Facility

In our MicroGraphic VTOL Simulator at New Mexico State University, alongcourse and crosscourse translational rates and/or accelerations (depending on the mode in effect) are controlled by a three-axis, spring-centered control stick mounted on the right-hand armrest. Alongcourse tracking is controlled by fore and aft stick displacement from a center detent, and crosscourse tracking by left and right stick displacement.

Rotating (twisting) the stick about its vertical axis controls the vehicle's yaw (crab) angle relative to the horizontal velocity vector. Vertical flight is regulated by a control operated by the pilot's left hand. The control is spring-centered and viscously damped and is operated by displacing the stick upward to ascend and downward to descend, thereby serving as a total-vertical-thrust control.

In the display shown in Figure 1, the vehicle's heading in the horizontal plane is displayed by a rotating compass rose that responds to both crosscourse control inputs and weather-vaning of the vehicle due to the effects of relative wind. A turn-rate index line is shown relative to top-dead-center of the display so that a desired heading can be captured by matching this index with the desired position on the rotating compass rose. Crosscourse and along-course rates and/or accelerations are displayed by a position predictor.
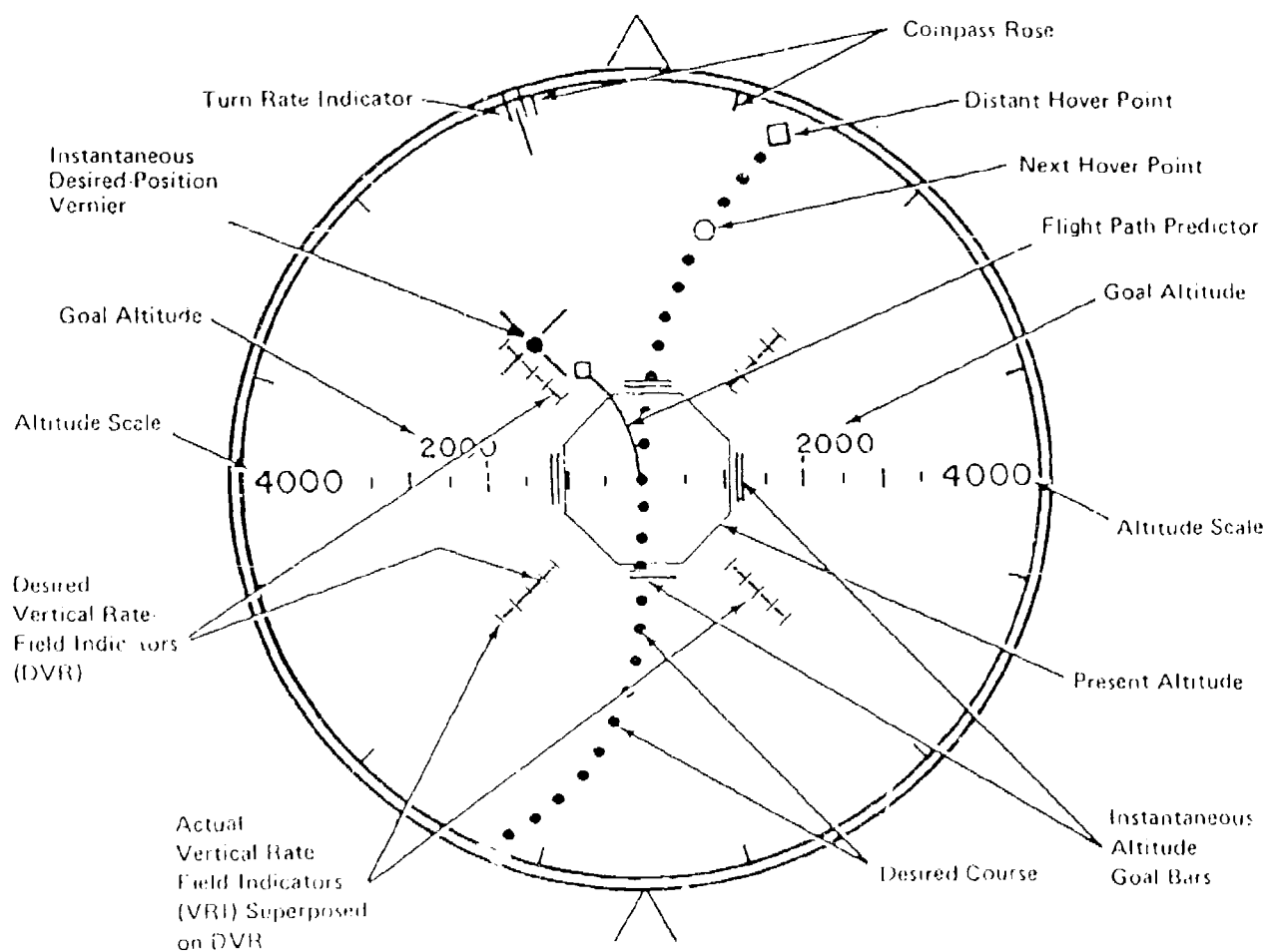

Figure 1. HOrizontally and VERtically INteGrated (HOVERING) display for vertical and translational instrument flight.

A target or desired flight path is acquired by placing the predictor on the Instantaneous Desired Position Vernier using control inputs from the three-axis side-arm control. Although the display is basically an inside-out presentation, it has frequency-separation characteristics analogous to those advanced by Roscoe (1968b; Roscoe et al., 1980) for aircraft attitude indicators. The predictor functions as an immediate indication of the imminent effects of the pilot's control inputs (high-frequency responses), whereas the closure of error between the target and the pilot's point of reference responds more slowly (low-frequency responses). Once a target has been acquired, the predictor should be kept on the target cross as it moves toward the pilot's point of reference.

When a downward-looking display is used to facilitate fore-aft and left-right control in vertical flight, the integration of altitude and vertical speed poses a difficult problem. In an early development of an HSD for use in helicopters by the US Army, Dukes (1970) provided a separate altitude scale along the side of the display (analogous to a dedicated airspeed indicator embedded in a forward-looking display). This did have the effect of reducing scanning time, but workload was still quite heavy, and unambiguously integrating the vertical dimension in a horizontal display was our objective.

Our solution was to encode altitude by the size of an octagonal box that dilates as altitude increases and constricts as altitude decreases, as would the absolute field of view seen through an octagonal hole in the floor of the cockpit. Altitude (size of the octagon) is read against a fixed scale that emanates left and right from the display center. The scale limits at the display's outer edge automatically increase by a factor of four as the simulated aircraft ascends through the momentary limits and reduce as it descends within the limits of the next larger scale. Vertical rates are shown by rate-field indicators (Majendie, 1960; Swartzendruber and Roscoe, 1980) that "flow" outward and inward with ascent and descent, respectively, at azimuth angles of 45, 135, 225, and 315 degrees.

Desired altitude is indicated by four sets of dynamic Instantaneous Altitude Goal Bars and by a static numerical indication of the current Altitude Goal (as might be assigned by air traffic control). Desired vertical rate is indicated by a set of four rate-field bars (orthogonal to the Actual Vertical Rate Indicators) that flow outward to call for a desired climb rate and inward for a descent rate. The desired and actual altitude indications move independently; hence, altitude control reduces to a pursuit tracking task. Similarly, vertical rate is controlled by matching the flow of the actual to the desired rate-field indications.

The requirement to display vehicle accelerations is satisfied by including translational accelerations in the second-order horizontal position predictor computations and optionally in an altitude predictor (not shown in Figure 1 but subsequently included in the display). Presenting acceleration terms in this way captures their benefits without increasing display clutter. The need for the pilot to deal with accelerations directly is further softened by reducing vertical control to first-order and translational control to a combination of first- and second-order. The pilot is unburdened even more by providing him various autopilot "cruise control" and "altitude hold" modes.

EXPERIMENTAL OPTIMIZATION

When the various tradeoffs just discussed have been resolved and the display configurations decided on, the control and display system design process is on its way but far from completed. What remains is the experimental optimization of literally dozens of dynamic variables embedded in the system. Once again the designer may or may not think of these parameters as experimental variables, but each must assume some value, and systematic multifactor experimentation is surer and potentially quicker than trial and error methods. Fortunately, many of the variables are not critical, and their parameters can be set on the basis of past experience, so the number of critical variables becomes manageable.

Holistic Experimentation

Consider the following list of variables potentially critical to pilot performance with our horizontal display for vertical and translational flight:

CO: Control order, translational and vertical
CG: Control gain, translational and vertical
CR: Vertical control gain reduction with increases in altimeter scale factor
PO: Flight path prediction order
PT: Flight path prediction time
MF: Vernier deviation indicator magnification factor
IP: Initial position error magnitude

Analysis and pretesting suggested that these variables were among the more critical and warranted primary experimental attention. To deal with even this relatively small number of variables using conventional factorial analysis of variance experimental designs would be prohibitive. An economical holistic multifactor approach was adopted, as advanced by Simon (1973, 1976, 1977a, 1977b, 1984; Simon and Roscoe, 1984).

Simon's holistic approach to multifactor problems involves a sequential strategy in which as many potentially critical variables as possible are screened, typically in an economical fractional factorial experiment, to arrive at a smaller number to receive further experimental optimization, typically using a still economical central-composite response surface design. In the optimization of a given system, an investigator's objective is to establish a quantitative relationship, or multiple regression model, between pilot performance and a set of system parameters. The estimated function of performance levels to system parameter levels is known as the response surface.

The procedures used to investigate response surfaces were originally developed by Box and Wilson (1951) for use in chemical research to determine the optimum combination of variables to produce the maximum yield of a chemical process. Response surface methodology (RSM) has since been shown to be practical in psychological research, especially in studies pertaining to human performance (Meyer, 1963; Simon, 1970; Williges and Simon, 1971; Clark and Williges, 1973; Scanlan and Clark, 1974; Scanlan, 1975; Clark-Dixon, 1976; Beringer, 1979; Scanlan and Roscoe, 1980; Randle et al., 1980; Roscoe and Eisele, 1980; Simon and Roscoe, 1984).

Among the numerous benefits from the use of RSM, the most notable are sampling economy and relative freedom from bias (Simon, 1970; Simon and Roscoe, 1984). Response surface designs are planned to minimize redundancy and to limit data collection to that really necessary (Simon, 1970). This is accomplished by collecting the fewest data sufficient to estimate the coefficients of the lowest-degree polynomial that yields an acceptable fit. For most behavioral response surfaces, a second-degree polynomial seems to be adequate. Freedom from experimental bias depends on setting the fixed values of controlled variables close to typical real-world conditions and sampling a range of realistic operational tasks.

Screening Variables: The Tatro Experiment

The eight variables listed above were included in a single 2^{8-2} (resolution-V) fractional factorial experiment (Tatro et al., 1983; Roscoe et al., 1984; Tatro and Roscoe, 1986). A resolution-V design was selected because of its relative economy and high resolution (as these designs go, resolution-V is considered very clean; Simon, 1977b). This particular design consisted of 4 blocks of 16 conditions, or 64 observations, per subject. In designs of this resolution, main effects are isolated (unconfounded) from one another and from first- and second-order interactions. However, they are aliased with third- , fourth- , and higher-order interactions. Third-order interactions and higher are assumed to be negligible; thus, main effects and first-order (two-factor) interactions are essentially unconfounded (Simon, 1973, 1976, 1977b, 1984).

Private pilots with no helicopter or other VTOL flight experience learned to fly the VTOL simulator in a relatively simple instrument departure procedure. Multiple regression equations for each of three performance measures (log RMS longitudinal, lateral, and vertical errors) revealed the relative contributions of each of the eight variables to the total performance variance for each measure. Five of the eight variables proved critical to performance: vernier deviation magnification factor, control gain, control order, prediction time, and tracking mode.

Of the five variables found to be critical in the screening study, the magnification factor of the vernier deviation indicator had the largest single effect, accounting for 25 percent of the variance in both longitudinal and lateral tracking. As magnification increased, tracking became more precise. However, as magnification increases, a tradeoff in the acceptable control/display ratio occurs. It was found that, for each 4 to 1 increase in display magnification, a control gain reduction of about 1/2 was needed to maintain an acceptable ratio. However, the optimum combination between control gain and magnification may differ for various flight tasks.

High control gain results in faster target acquisition but less time on target. Low control gain accommodates the fine adjustments needed for keeping on target but causes slower target acquisition. Thus a compromise is needed between the two extremes. In a flight task such as an intercept approach, high gain would be preferable; while in an air-sea rescue mission, low gain would help the pilot. Thus the optimum sensitivity of control is a compromise between the high gain required to reduce acquisition time and the low gain required for fine adjustments (Poulton, 1974), and the point of best

compromise shifts with the magnification factor in use.

Control order proved to be important in the screening study for all three performance dimensions, with second-order control being most effective. In the literature on the effects of control order on tracking performance, most experiments show first-order control superior, while other studies indicate second-order control to be easier (Poulton, 1974). These contradictory results, once again, are most likely task-related, and such being the case, control order needed to be optimized across various flight scenarios of increasing complexity.

Prediction time was also found to   a significant contributor to the observed performance variance. In other contexts, optimum prediction time has been found to vary from task to task. Furthermore, short prediction times produce a tendency for overcontrolling the vehicle; the longer the prediction time, the smoother and slower the control inputs (Beringer et al., 1975). Hence, short prediction times would be better with large errors, and long prediction times with small errors. Thus prediction time needed to be evaluated across different mission scenarios, especially with the addition of an altitude predictor following the completion of the screening phase.

The last critical variable in the screening study was tracking mode. Pursuit tracking has consistently been shown to be superior to compensatory tracking (Poulton, 1974); however, practical limitations have dictated the use of compensatory presentations. In pursuit tracking, independent indices of both target and vehicle movement are presented against a common, fixed frame of reference, whereas in compensatory tracking only the relative position of target to vehicle (or vice versa) is displayed, thereby resulting in a single index of error. Our display has a feature that transforms the compensatory tracking presentation into what we have termed a quasi-pursuit display, an extrapolation of the work of Bauerschmidt and Roscoe (1960).

In the quasi-pursuit tracking presentation, the position error is allotted to both the target and vehicle (instead of the standard single-error compensatory configuration), creating an appearance of independent movement. In the terminology of Roscoe et al., (1981b), a target-referenced compensatory (TRC) presentation, a vehicle-referenced compensatory (VRC) presentation, and a 50-percent-TRC/50-percent-VRC (quasi-pursuit) presentation were compared. The fraction of error allotted to either the target or vehicle can be continuously varied, but only the two extremes and the 50/50 combination were evaluated. The 50/50 mode resulted in significant improvement in transla-tional tracking.

Optimizing the Response Surface: The Wiedemann Experiment

The screening study had shown five variables critical to the performance of a relatively simple instrument departure maneuver. However, there is evidence in the literature that the effects of some of those variables can be task dependent (Chernikoff et al., 1960; Poulton, 1967, 1974; Ziegler, 1968; Roscoe and Kraus, 1973; Warner et al., 1976; Simon and Roscoe, 1984). To investigate the effects of task variation, and thereby obtain results of greater generalizability, three flight scenarios of 35 seconds each were used in a central composite response surface experiment (Wiedemann and Roscoe, 1985).

Scenarios. In Scenario 1, subjects were presented with a VTOL takeoff task involving precise altitude control with some crosscourse maneuvering. For the altitude profile of the flight, subjects initially started from a stationary point on an aircraft carrier. During the first four seconds, the aircraft was to ascend to 15 feet and fly level for five seconds. During the last 26 seconds of flight, the aircraft was to ascend rapidly from 15 feet to 400 feet, holding a constant heading away from the ship.

Scenario 2 involved an approach and landing task calling for precise control in three dimensions. The altitude subtask involved a level-descend-level-descend sequence starting at 100 feet, dipping below 60 feet, and then descending to zero feet. In this sequence the pilot had to negotiate one scale change when descending through the 60-foot altitude. For the translational subtask, a straight-turn-straight-turn-straight sequence was followed, calling for precise crosscourse and alongcourse tracking.

Finally, in Scenario 3, the standard instrument departure task used in the screening study was reevaluated to confirm or refine the previous results and estimate the quadratic components of the response surfaces. The task involved a constant-rate climbing turn to the right from 400 to 950 feet in altitude and 0 to 35 degrees in heading.

Subjects. Although we have observed no evident transfer from previous flight experience in fixed-wing airplanes or helicopters to performance in our VTOL simulator (pilots and nonpilots show comparable learning curves), it is possible that prior flight experience has both positive and negative effects that tend to cancel one another. For the optimization experiment, 20 right-handed male nonpilots were pretested in the VTOL simulator, and 12 were selected to form four stratified groups of three subjects each, respectively matched to minimize within-group and maximize between-group variances. One subject from each group was then assigned to each of the three scenarios to form three matched groups.

Experimental design. For each of the three flight scenarios, the same five-factor central-composite design was used. A 2^{5-1} (resolution-V) fractional factorial sampling was augmented with axial and center points to complete the central-composite response surface design (Simon, 1973). With this design, main effects are confounded with third-order (four-factor) interactions, and first-order (two-factor) interactions are confounded in second-order (three-factor) interactions. Because three-factor and higher interactions are usually negligible, main effects and first-order terms are essentially unconfounded.

Results. The experiment showed that the relative importance of the five manipulated control and display factors varied greatly as a function of flight task. This was anticipated because the three flight profiles imposed vastly different control and attentional demands. The landing and takeoff scenarios consisted of complex sequences of turns and straight segments combined with ascents and descents, resulting in the emergence of control order (linear and quadratic components) as the dominant factor. Decreasing the acceleration component of the control-order fraction resulted in more precise tracking in the more complex tasks, whereas increasing the acceleration component was beneficial in the simpler task.

The other major factor in the landing and takeoff scenarios was the quadratic prediction-time component. When the response surfaces for prediction time are graphed for these scenarios, U-shaped surfaces emerge with short and long prediction times resulting in increases in tracking error. Again the nature of the flight tasks would seem to be the major reason for the shape of the functions. Short prediction times resulted in overcontrol of the vehicle when precise tracking was required, whereas long prediction times resulted in undercontrol of the vehicle.

In contrast to the screening experiment, the effects of the other three experimental factors were relatively small. This result can be attributed directly to the dominance of control order. With pure acceleration (second-order) control, performance deteriorated such that the levels of the other factors became unimportant. If control order were kept at a fixed optimum level, we would expect the other factors to have significant effects once again. This situation emphasizes the need for multifactor experimentation. The interactions among variables are so complex that a reductionist study would only give incomplete and probably, if not certainly, biased estimates of the response surfaces.

Results from the standard instrument departure scenario confirmed the results found in the initial screening study. In this scenario the effects of all five experimental factors were significant. An interesting result was the fact that the linear terms of the model accounted for the majority of the variance, whereas the quadratic components of the regression models had significant effects in the more complex flight tasks. This would indicate the need for estimating second-order models in approximating surfaces for complex tasks, which are the norm for VTOL flight.

Ranges of acceptable values were evident for all five variables, within which a single set of values would yield near optimum performance on all tasks. However, because the more complex scenarios imposed greater time-sharing demands than the standard instrument departure, a composite model based on radial tracking errors for those scenarios would be the indicated choice as a guide in system design. For all variables except prediction time, a single value can be selected that falls within the optimum range. As in the case of vertical control gain, prediction time should be adjusted automatically with changes in altitude scale factor.

LIMITATIONS, QUESTIONS, AND SUGGESTIONS

Experimentation of the kind just reviewed allows several dynamic display and control design variables to be optimized for a hypothetical aircraft having specific performance characteristics. Unfortunately not all such results generalize to aircraft having different characteristics or missions requiring grossly different maneuvers. So, when each new aircraft is being designed, values have to be determined for all such variables, and some relatively economical and logistically manageable optimization strategy must be adopted. In fact, the experiments described primarily serve to demonstrate the feasibility of a holistic experimental approach to control and display system design. The generalizability of their specific findings is limited.

Firstly, the design variables screened and optimized represented a relatively small subset of those potentially critical to pilot performance. Secondly, the horizontal display was used in isolation, when in fact one would expect its characteristics to interact with those eventually settled or for the companion vertical display. Thirdly, the selection of display symbology and motion relationships, while generally based on experimentally supported control and display "principles," necessarily involved arbitrary decisions in those cases in which no clear guiding principles exist. An example of the last limitation involves the direction of motion of the new symbology for altitude and vertical rate.

Direction of Altimeter Motion: The Trujillo Experiment

Among the design issues that have to be resolved is how to achieve directional compatibility between control movements and the immediately resulting display indications. Compatible motion relationships are critical not only to the precision of continuous control but also to the prevention of control reversals, displacing a control in the wrong direction because the movement of a display element is misinterpreted. Most people expect moving display elements to represent their own movements. In some cases these expectancies are so universal that they have been termed "population stereotypes."

Our unique method of integrating altitude and vertical rate information in a horizontal display involved an octagonal "box" symbol that dilated as the vehicle ascended and constricted as it descended, as would the visible area of ground viewed through a downward-looking porthole in the floor of the cockpit. Alternatively, one could think of the box as an octagon painted on the ground, in which case it would constrict with ascent and dilate with descent, the converse of our original concept. Inevitably there are some who find each arrangement more "natural," just as there are map-turners and north-uppers in approximately equal numbers.

When control-display arrangements conform to population stereotypes, reaction times are shorter, there are fewer control reversals, control movements are more precise, and the operator can learn to operate a system faster. Humans are remarkably adaptable creatures that can learn to operate a control-display system that requires control movements in directions opposite to those expected. The problem arises when a situation occurs that requires extremely fast reactions under workload pressure or distraction. When this happens, learned habits often break down, and control reversals occur.

When there is no obvious population stereotype, experimentation is in order. The alternative directions of motion of the altitude and vertical rate symbols were compared in an experiment involving a stressful side task and a primary terrain following and avoidance task in which unpredictable changes in vertical flight path angle were called for (Trujillo and Roscoe, 1985). The consistent finding was that whichever way the altimeter moves makes little difference so long as the vertical rate fields move in the same direction. When the altimeter and rate fields move in opposite directions, control reversals are more frequent, and tracking performance suffers. With compatibility in altitude and vertical rate indications, pilots can be trained to interpret the display in either way without difficulty.

A caveat is in order concerning the generalizability of this conclusion. Whenever stereotypic response tendencies are the object of investigation, the subject population is a critical consideration. For this initial study, flight-naive subjects were sampled. Hence, it would be risky and unwise to count on the same stereotypic response patterns from experienced pilots. However, because the display is new to everyone, and the dynamics of our generic VTOL simulation do not represent any specific real-world aircraft, we have observed informally that pilots, whatever their experience, require about the same amount of training as nonpilots to fly the simulator equally well.

Control and Display Augmentations

The term control augmentation can refer both to the reduction in control order and to inertial stabilization of the vehicle to counter movements not called for by control inputs. In general, higher orders of control (those greater than second-order) should be allocated to onboard processors, leaving the pilot responsible for lower control orders. Providing first-order vertical rate control and translational control that is about a 1.5-order mixture of rate and acceleration outputs is not an unreasonable arrangement with the current state of the art. Experimental evidence is converging in support of this combination.

Inertial counteraction of vehicle accelerations not called for by the control system is also not an unreasonable design requirement. In a report prepared for the US Army Aviation Research and Development Command (1980), specifications for the advanced Scout helicopter included both a heading-hold function and a hovering flight mode. Augmentations of aircraft control systems that counter inputs to the system not called for by the pilot are quickly becoming a reality at an operational level. In our system, longitudinal, lateral, and vertical accelerations as well as heading were all stabilized in the simulated vehicle model. Some worry that too much control authority is lost in systems of this sort, but a great deal of "flyability" is gained with a consequent reduction in training requirements.

Maintaining an acceptable control/display ratio without compromising control authority is a problem that almost necessarily involves varying control gain and thereby limiting a pilot's control authority in some way. A limited authority mode that can be instantly aborted would appear to be a promising candidate. Adapting a rate-hold function by the addition of scaled-down vernier acceleration inputs was the option tested. Engaging the rate-hold mode has two effects: First, it serves to hold constant the vehicle's velocities at the time of engagement. Second, after the rate-hold mode is engaged, the control stick becomes a fine-tune control that allows small acceleration outputs to null position and rate errors.

These changes convert the system to second-order control while also reducing gain. A more complex implementation of this method could solve the control/display ratio problem while still maintaining the pilot's ability to assume full control authority at any moment. For example, if minimizing tracking error becomes essential for mission success (as in the approach to a shipboard landing), display magnification can be dynamically increased while reducing the control gain. If properly employed, such a control system logic could achieve a high degree of tracking accuracy without any increase in pilot workload.

Programming dynamic changes in display configuration may ultimately be applied to other variables in addition to scale factors. As one example, prediction time is a strong candidate. As mission phases change, optimum prediction times vary. They also depend on the current prediction order and display magnification factor. With such complexities, system designers often choose either fixed parameters that provide acceptable but not optimum performance or manually selectable modes. Evidently the interrelationships among display variables are too complex for independent selection of variable levels in real-time operations. Consequently, programming a system to select optimum display configurations automatically for various mission phases seems to be indicated.

The term _display augmentation_ can also refer to the superpositioning of imagery from downward-looking sensors or computer-generated ground maps from a digital data base on the horizontal display, just as forward-looking sensor imagery can be superposed on a contact analog vertical situation display. In so doing the big picture of our skeletal display system would be fleshed out to provide the more highly detailed outside information needed for immediate local orientation, target detection and recognition, and vehicle and weapon control. Precise and safe VTOL flight operations without any direct outside view from the cockpit are within reach.

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McDonnell-Douglas Astronautics Co.
St. Louis Division
Box 516
St. Louis, MO 63166

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Human Factors
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Washington, DC 20546

Dr. Stanley Deutsch
NAS-National Research Council
(COHF)
2101 Constitution Avenue, NW
Washington, DC 20418

Defense Technical Information
Center
Cameron Station, Bldg. 5
Alexandria, VA 22314

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

Dr. Robert Wherry
Analytics, Inc.
2500 Maryland Road
Willow Grove, PA 19090