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TECHNICAL REPORT

ARL

ADVANCED INTEGRATED AIRCRAFT DISPLAYS AND AUGMENTED FLIGHT CONTROL

VOLUME 1 : SCIENTIFIC FINDINGS

STANLEY N. ROSCOE, JANICE E. EISELE, CRAIG A. BERGMAN

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Institute of Aviation

University of Illinois at Urbana-Champaign
Willard Airport
Savoy, Illinois
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20 ABSTRACT (Continue on reverse side if necessary and identify by block number)

This integrative report is divded into two volumes. Volume I introduces a classification of aircraft displays and controls, reviews problems that have plagued their evolution, and advances the pilot's task hierarchy as a conceptual framework within which available information can be abstracted, integrated, and applied to the design of displays and controls. In particular, Volume I constit[illegible] a bringing together and integration of the findings from the various [illegible]torical lines of investigation associated with quickening and

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CONTENTS

VOLUME I SCIENTIFIC FINDINGS

VOLUME II APPENDICES

CONTEXT

The Aviation Research Laboratory of the University of Illinois is investigating synthetic imaging displays and computer-augmented flight control for the Office of Naval Research. Mr. Gerald Malecki, Associate Director of Aviation Psychology Programs, is the technical monitor of the research. Professor Stanley N. Roscoe was the principal investigator during the initial phase of study and experimental apparatus development covered by this report. Professor Robert C. Williges is serving as principal investigator for the continuing effort while Professor Roscoe is on academic leave during 1975-76.

The research is directed toward (1) the isolation of minimum sets of visual image cues sufficient for spatial and geographic orientation in the various ground-referenced phases of representative flight missions, (2) the generation and spatially integrated presentation of computed guidance commands and fast-time flight path predictors, and (3) the matching of the dynamic temporal relationships among these display indications for compatibility with computer-augmented flight performance control dynamics, both within each ground-referenced mission phase and during transitions between phases. The investigative program draws selectively upon past work done principally under ONR sponsorship or partial sponsorship, including the ANIP and JANAIR programs.

Organization of Report

This integrative report is divided into two volumes. Volume I introduces a classification of aircraft displays and controls, reviews problems that have plagued their evolution, and advances the pilot's task hierarchy as a conceptual framework within which available information can be abstracted, integrated, and applied to the design of displays and controls. In particular, Volume I constitutes a bringing together and integration of the findings from the various historical lines of investigation associated with quickening and unburdening, contact analog displays, predictor displays, frequency-separated displays, and performance control systems.

Volume II contains reports detailing the past year's hardware efforts. Hardware specific to Phase II simulation and experimentation was designed, built, and installed. Volume II describes equipment necessary to continuing research on computer-augmented controls and computer-generated displays. Appendix A reports the design and installation of a digital control system for reduced order, decoupled control of an aircraft simulator (Daly, 1975). A real-time scan converter for computer-generated visual simulations is described in Appendix B (Collins, 1975). Another hardware development applicable to computer-generated visual simulations, a peripheral device for linear coordinate transformation, is detailed in Appendix C (Ruby, 1975).

Program Progress and Plans

During Phase I of the current contract, the Aviation Research Laboratory systematically investigated the relationships between the movement of the controls and the response of the airplane and demonstrated substantial improvement in pilot performance as a consequence of their reorganization. By the completion of Phase I, all planned control modifications, specifically the digital control system (Appendix A), have been incorporated into the GAT-2 simulator. No additional work on this task is contemplated for the initial year of Phase II.

To study experimentally the effectiveness of alternate sets of visual cues, the Aviation Research Laboratory has developed a highly versatile computer-generated display system to present dynamic pictorial images either on a head-down, panel-mounted CRT or on a head-up television projection to a large screen mounted in front of the pilot's windshield on the Link GAT-2 simulator. Due to the great flexibility of the pictorial display, visual cues and flight status information can be manipulated experimentally. Experimentation to isolate the visual cues sufficient for approach and landing is in progress.

The incorporation of predictive indications (Kelley, 1968) of successive future states is currently under investigation during Phase II. Experiments will be conducted to determine the number and temporal spacing of flight path predictors to be integrated into the forward-looking flight view. Determination and software implementation of command guidance symbology compatible with the synthetic forward-looking contact analog and predictive flight path presentations will also be undertaken. It is the ultimate objective of this program to develop, during the second year of Phase II, a reconfigured cockpit with integrated sensor and computer-generated imaging displays and computer-augmented controls.

INTRODUCTION

The rapid development of aircraft technology, in a curious yet direct way, has increased the urgency of research on pilot performance as an information processor and the development of display and control design principles to enhance his performance. In the new generation of high-speed, multi-mission aircraft the role of the pilot has changed substantially. New system elements typically require the man to be an information manager or a fast decision maker as opposed to a direct controller of flight variables. Adjustment to the new demands has been greatly assisted by innovations in display and control technology and the inclusion of advanced computers on board. These sophisticated innovations have increased the degrees of freedom in function allocation and display and control system design. Yet, to capitalize on these opportunities, improved methodology and better understanding of human performance are necessary for a wise use of these additional degrees of freedom.

As aircraft become more sophisticated and their missions more demanding, there is an inevitable increase in the pilot's dependence on artificial devices for sensing and display of information about aircraft performance and for control of the aircraft in flight. Figure 1 illustrates how displays and controls provide the interfacing between the pilot and the aircraft. Conventional interfaces among aircraft dynamics, displays, controls, and pilot are depicted by solid lines. Computer assistance can be applied as shown by the dashed lines. Many functions previously performed by crew members have been allocated to onboard computer systems during recent years (Semple, Heapy, Conway, and Burnette, 1971).

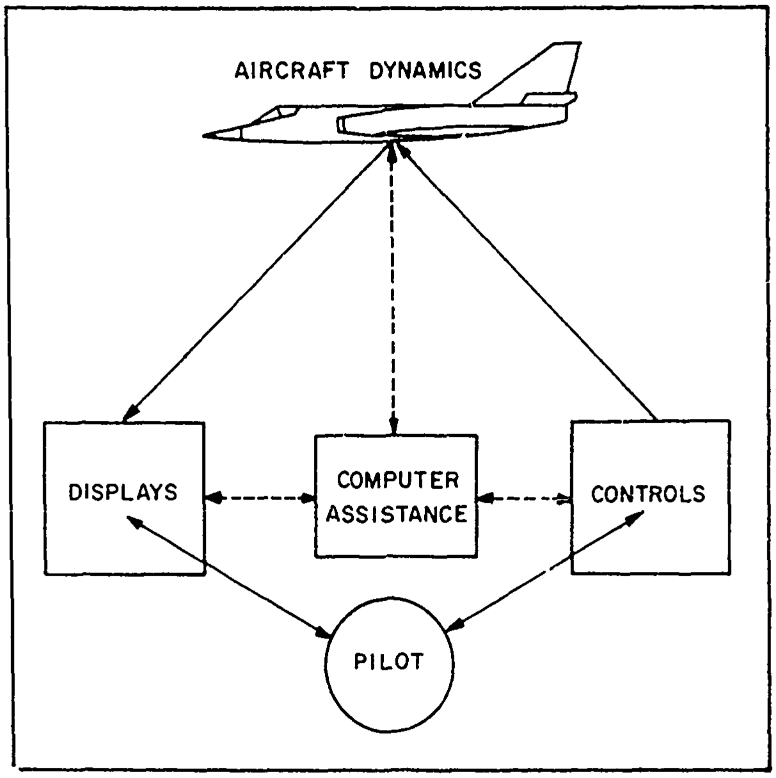

Figure 1. Diagram of pilot and aircraft interfaces.

With ever increasing air traffic densities, ever improving aircraft performance, and a requirement for all-weather operation, the optimization of pilot-aircraft interfaces carries a high premium. In today's aircraft the pilot must translate long-term mission objectives into instantaneous subgoals for each individual instrument, typically in terms of scale or needle positions and rates. To deal with the space-time relationships between the mission goal and the instrument subgoals the pilot must understand the complex, often devious, dynamic transformations between control inputs, aircraft responses, and instrument indications. A computer-generated integrated aircraft information display system, in combination with computer-augmented controls, could simplify these transformations with a related reduction in pilot workload and an increase in operational effectiveness.

To investigate the information needed and the coding of each item, a concept of the pilot's task must be formed. One approach is to determine the specific information requirements for a particular flight in a particular airplane and to judge the adequacy of a particular display panel against these. However, such an approach requires eternal iteration, and there is no way of assuring that all likely missions for any given airplane will be provided for in anything like an optimum manner. A more systematic approach is needed. Information requirements must be determined by examining mission requirements, aircraft system functions, decisional, procedural, and perceptual-motor crew functions, and associated performance criteria.

Many analyses of pilot information requirements have been made, and by comparing the results of some of the more systematic (Williams, 1947/71; Ritchie, 1960; Dunlap and Associates, 1962; Ketchel and Jenney, 1968), it can be seen that there are marked differences of opinion among pilots and investigators as to the information required for common missions. One may conclude that lists of pilot information requirements, as they exist, are inadequate for deciding what information to include in flight displays.

Apart from differences of opinion regarding the information content required for the effective execution of commonly performed mission segments, there is no disagreement among pilots and investigators concerning the inadequacy of current instrument presentations for uncommon flight operations, such as nap-of-the-earth helicopter operations at night or zero-visibility carrier landings. Whenever new types of missions are contemplated, whether special purpose military operations or modified terminal area procedures designed to expedite traffic flow at civil airports, both new means of sensing information and new cockpit displays are typically required. Modern programable computing and display technology now affords a more general approach to flight information sensing and display.

To succeed in applying modern technology to these long-standing unsolved problems, what is known from research and experience in specific contexts must first be abstracted through analysis and then integrated through synthesis. Even if all of the pilot's information requirements were exhaustively known, and the required dynamics for each displayed variable specified quantitatively, creative design would still be required to embody those requirements in a clearly encoded display. The transformations between information to be displayed and its optimum coding remain obscure because lists of information requirements do not imply anything about the relationships among items of information. Information should be considered as an organic, dynamic system, not as discrete items.

Williams (1947/71) conducted a generic 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.

Williams proceeded to conceive the embryo of such a scheme, and Carel (1965) and Roscoe (1968; 1974) have developed his concepts as summarized in the following discussion.

PILOT'S TASK HIERARCHY

Williams viewed the overall task of the pilot as the linking of discrimination and manipulation events to bring the aircraft to the final mission goal. A flight mission, like any other human activity, is goal directed, as shown in Figure 2 (adapted from Carel, 1965). The planning of a flight starts with the completion of the mission and requires the pilot to establish the various subgoals that must be antecedent to the accomplishment of the overall mission goal. Thus, the pilot has to determine, moment-to-moment throughout a flight, the altitude to fly, the heading to fly, the speed to fly, how long to fly, and the operating condition of his aircraft and its subsystems.

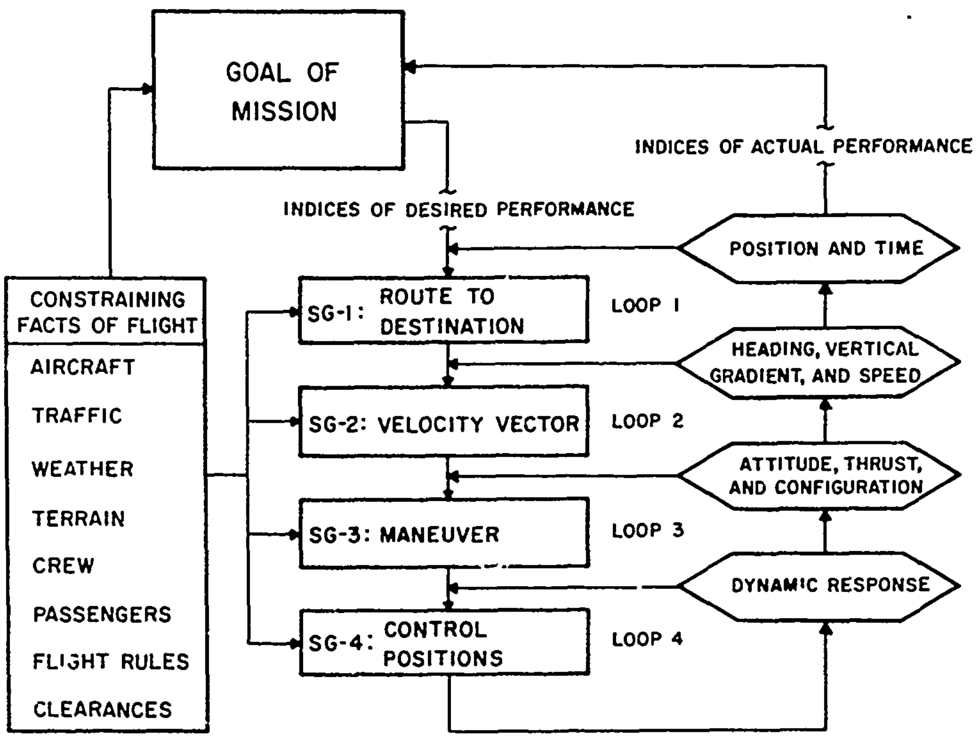

Figure 2. The hierarchical nature of the flight task.

To set up all the subgoals, the pilot must take into account the constraining facts of flight: the condition of the aircraft itself; the traffic, which may be friendly or unfriendly; the weather; the terrain over which he is flying, or against which he is delivering weapons; other crew members, if any, and their condition and tolerances; passengers, if any; and the rules and clearances that determine the constraints of flying in the local airspace, whether it be friendly domestic airspace or combat airspace.

The tasks that a pilot must perform if he is to complete a specific mission in a specific airplane include, first, the selection of indices of desired performance leading to all required subgoals, taking into account the constraints listed, and, second, controlling the aircraft to match its actual performance to the desired performance indices he has set up. Because the control of an aircraft is hierarchical in nature, as diagramed in Figure 2, the pilot's job is complicated by the fact that several transformations are required between what he sees and hears and how he must move the controls at the lowest loop in the hierarchy.

If the relationships between the constraints of flight, the indices of desired performance, and the control of actual aircraft and subsystem performance were simple, there would be little for the pilot to do; but they are not simple, and the analysis of the transformations that the pilot must make in performing a given mission defines not only the information that he must receive from his displays or the outside world but also the things he must do with that information to control his aircraft successfully.

Short of the submarine, the helicopter, the the leaning-wheel grader, the fixed-wing airplane is among the most contrary vehicles man has been called upon to control. When flying a specific course at constant altitude, the pilot is operating a machine that requires fourth-order lateral and third-order longitudinal control, as represented in Figure 3. The lateral, or crosscourse, aircraft dynamics constitute a fourth-order system wherein the response to a control deflection creates a roll acceleration ($\ddot{\phi}$), roll rate ($\dot{\phi}$), bank angle (ϕ), heading (ψ), and displacement (D). In the third-order longitudinal (vertical) mode, a control deflection initially creates a pitch acceleration ($\ddot{\theta}$), and its integrals are successively pitch rate ($\dot{\theta}$), which is roughly proportional to vertical acceleration ($\ddot{h}$), pitch (θ), which is roughly proportional to vertical speed ($\dot{h}$); and altitude (h).

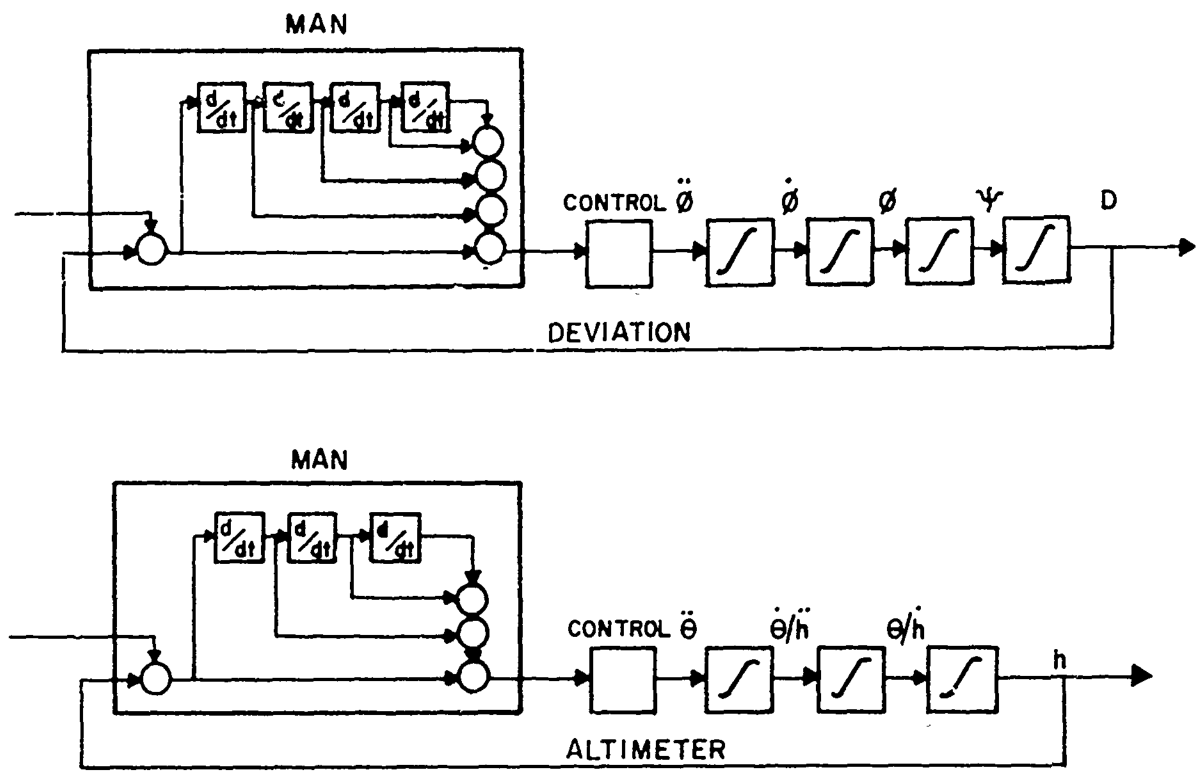

Figure 3. The theoretical manned aircraft.

Theoretically, one would be tempted to believe that the pilot operates as shown on the left side of Figure 3. That is, for the two controlled dimensions he must perform seven differentiations and nine summations continuously to fly the aircraft in a stable manner, as these functions are all required for stability. The implication of Figure 3 is that the course deviation needle and altimeter provide sufficient information that the pilot can obtain not only displacement, but velocity, acceleration, and the higher-order terms. From experience, this sort of sensing from these instruments is impossible.

A more realistic representation is shown in Figure 4. Roll acceleration cues are available proprioceptively as kinesthetic cues from the controls directly and vestibular cues from the roll accelerations acting upon the pilot himself. Roll rate and bank angle can be seen from the

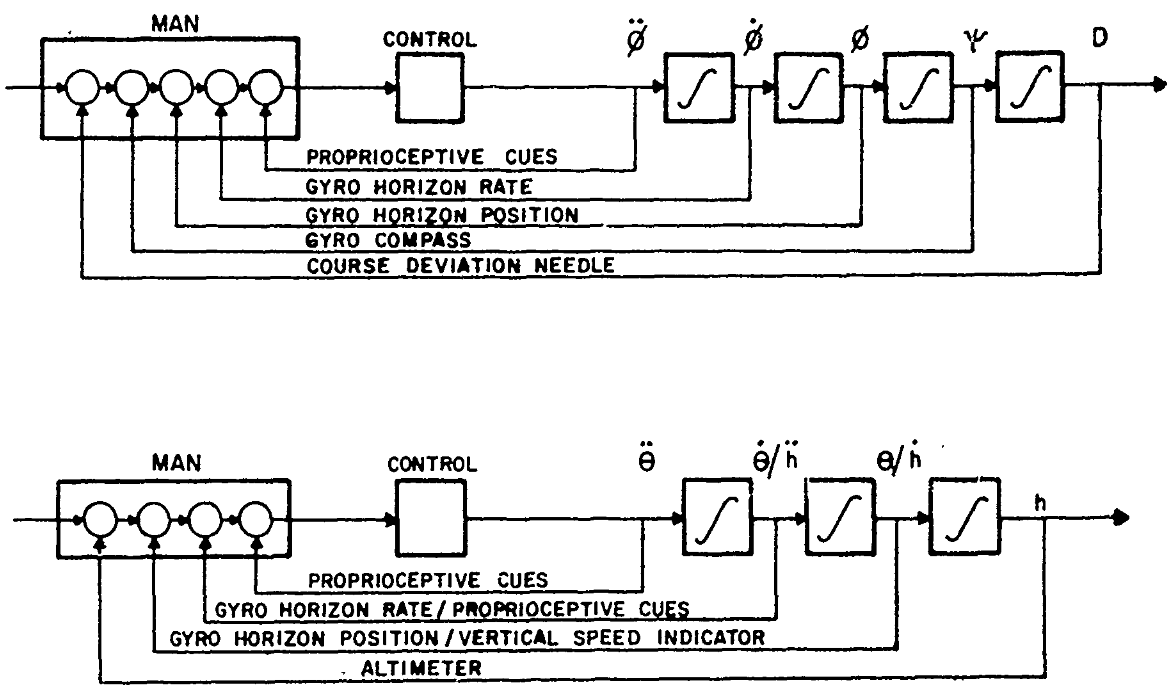

Figure 4. The practical manned aircraft.

rate and position of the gyro horizon, heading can be obtained from the gyro compass, and crosscourse error, or distance off course, can be seen on the course deviation needle. Longitudinally, pitch acceleration can be sensed, again proprioceptively, and pitch rate and position can be observed on the gyro horizon. Vertical acceleration can be sensed kinesthetically, vertical speed can be read on the vertical speed indicator, and altitude is obtained from the altimeter.

Within the overall task hierarchy the major task clusters deal with the iterative asking and answering of four questions:

1. What should be my route to my destination, and where am I with respect to my desired route and destination?

2. What should be my velocity vector, and what is it now?

3. What should be my attitude, thrust, and configuration, and what are they now?

4. What should I do with the controls to correct discrepancies that may exist in 1, 2, and 3?

An integrated display and control system should present the information necessary for the pilot to answer these questions quickly and accurately throughout a mission.

Many of the functions that comprise the flight control of a modern airplane could be performed at some level either automatically or manually. Design tradeoffs involving function analysis and allocation can result in giant swings in both the operational effectiveness and life-cycle costs of aircraft, particularly in the areas of pilot training and proficiency maintenance. The reorganization of the manual control of airplanes to simplify the pilot's job through the reallocation of transformation functions should precede consideration of the synthesis of displays.

COMPUTER-AUGMENTED CONTROLS

Prior to the present decade, the response of an airplane to manual control inputs had remained substantially unchanged throughout the history of aviation. The shape and kinematic behavior of the cockpit control mechanisms had been improved, the forces required to operate the controls had been modified favorably, and some stability augmentation had been added; but there had been little systematic effort to reorganize the manual control task or to improve the dynamic relationships between manual control inputs made by the pilot and the resulting aircraft responses.

Some airplanes feature control augmentation devices that provide softly coupled automatic coordination and lift compensation in turns. However, efforts to improve safety and reduce attention required for flying duties during the performance of other tasks have been restricted to the refinement of handling qualities criteria for aircraft with traditional control behavior (Cooper and Harper, 1969; Gilruth, 1943; Phillips, 1949) and to the ever increasing use of autopilots. This has resulted in the retention of the stick, or yoke, and rudder pedals as devices for controlling, not the airplane directly, but rather its ailerons, elevator, and rudder -- the positions of which are of little personal interest to the pilot.

The dynamics of the airplane are complex, being determined by gravitational, inertial, and aerodynamic forces. The fixed-wing aircraft has six degrees of maneuverability, three translational and three rotational.

These six degrees of freedom are not independent but, rather, are coupled into characteristic response modes, one or more of which is usually unstable due to basic airplane design. These modes are excited by turbulence or by control deflections. Their dynamics change slowly with fuel consumption, more rapidly with airspeed and altitude, and abruptly with payload release, configuration changes, and contact with the runway.

In general, depending on an airplane's configuration, the pilot's workload in maintaining control is affected by variations in gross weight, airspeed, and power, as well as aerodynamic and inertial coupling among the three aircraft axes. A thorough stability and control analysis of an airplane involves the assessment of a large number of force and moment coefficient derivatives that represent the change in aerodynamic forces and moments resulting from changes in airplane attitude, control deflections, and power. Although the pilot is not usually aware of the subtle contributions of each coefficient to the control of his flight path, he is nevertheless involved with continuous coordination of the controls to achieve and maintain a desired flight condition.

In addition, in limiting flight conditions involving physical constraints or partial airflow separation on aerodynamics surfaces, large-scale changes in control behavior occur. For example, in normal flight, lateral displacement of the stick controls angular rate about the longitudinal axis of the aircraft, while the rudder pedals are used to control yaw. However, during most of the takeoff run and landing roll after touchdown, displacement of the stick has no effect on roll rate but does have an immediate and pronounced effect on yaw. Worse yet, this effect is in the opposite direction to that normally expected; right stick causes left yaw! Furthermore, when the airplane is stalled, the rudder pedals become the effective control for roll. And so it goes.

Function Allocation

A good starting point in approaching any system design problem is first to determine the functions the system must perform to accomplish its given mission and then the best distribution of those functions between the people in the system and automatic mechanisms. If control of the six degrees of freedom of the aircraft constitutes the functions to be performed, the first design task is to decide on a basis for distributing control authority and responsibility for these functions between the pilot and the automated portions of the control system.

At least in theory, it would be possible to provide means of control that would give the pilot authority over position, rate, acceleration, or rate of change of acceleration with respect to any or all of the six degrees of freedom. The farther along this list his authority extends, the greater his responsibility for coordinating moment-to-moment control inputs. As his control authority shifts in the opposite direction, the system becomes increasingly automatic, and his direct control responsibilities diminish (Bergman, Sivier, and Roscoe, 1973).

The essential problem appears to be that of determining the point at which the pilot should interface with semiautomatic controls to minimize the difficulty of his control task without depriving him of the minimum essential control authority to counter any reasonably likely flight contingency. To the extent that he can be removed from the inner loops of control, where he performs integrating and coordinating functions for virtually every subsystem of the airplane, he will be unburdened of the routine of repetitive manipulation, and his performance will be more precise and less variable (Kelley, 1968).

Birmingham and Taylor (1954) proposed a design philosophy for man-machine control systems. Incorporated in this philosophy are the concepts of aiding, quickening, unburdening, and the order of control that man must perform. The essence of the philosophy is that, whenever possible, man should be made to operate as a zero-order controller; he should be required to perform functions no more complex than the simple transmission of a displayed position to a control handle. To the extent that he must perform integrations, differentiations, and summations, he is not performing in the simplest manner.

Distribution of Control Authority

Ince and Williges (1972/74) studied the human operator's adaptive behavior in manual control with slowly changing system dynamics. In their first experiment, the dynamics changed from rate to acceleration control. In a second experiment, the control stick sensitivity slowly increased or slowly decreased from a standard level. Tracking performance on a compensatory task demonstrated that the human operator lags in adapting to the changing system dynamics, but he does adapt when given sufficient time. As the rate of change increases, the human operator needs less time but a larger absolute change for detection of the changing system dynamics.

It is not surprising that both gradual and abrupt changes in flight control dynamics create training problems and also limit the ultimate operational effectiveness of skilled pilots. It is evident that eliminating both the subtle changes in airplane control dynamics, as studied by Ince and

Williges, and drastic changes, as encountered with asymmetric loss of thrust, would relieve both training and operating problems. The evolving principles of control configured vehicle design address precisely this objective. A control configured vehicle (CCV) depends upon synthetic augmentation for stability of control, thereby making possible favorable design tradeoffs in areas such as structural configuration, performance, and ease and precision of manual flying.

A study of the parametric combinations of 16 manual control system modifications by Kraus (1973) led to the selection and experimental evaluation of position control of bank angle and rate of climb or descent, automatic yaw coordination, and lift compensation in turns. This system, referred to as a performance control system (PCS), was tested in a Singer-Link GAT-2 simulator (Kraus and Roscoe, 1972; Roscoe and Kraus, 1973), and subsequently a flight qualified experimental system having similar variable characteristics was installed and tested in a Beechcraft Twin Bonanza research aircraft (Bergman, 1973; Bergman, *et al.*, 1973; Bergman, 1975; in press).

Flight Performance Control

A model of the PCS system simulated by Kraus and developed and flight tested by Bergman is shown in Figure 5. A control configured Twin Bonanza research aircraft with this PCS installed is currently certificated for normal flight operations with few procedural restrictions. In this system, some of the feedback paths, instead of being sensed by the pilot, are now combined to drive the flight controls (control cables) directly, eliminating the pilot from the inner, higher-order, control loops. Because the controlled elements are now bank angle and vertical speed, the outer feedback paths carry these variables; the remaining system elements of Figure 5 are carried by dashed lines.

The innermost path of proprioceptive feedback is replaced by control displacement signals, and the attitude rate and position signals are replaced by gyro signals with lead compensation incorporated.

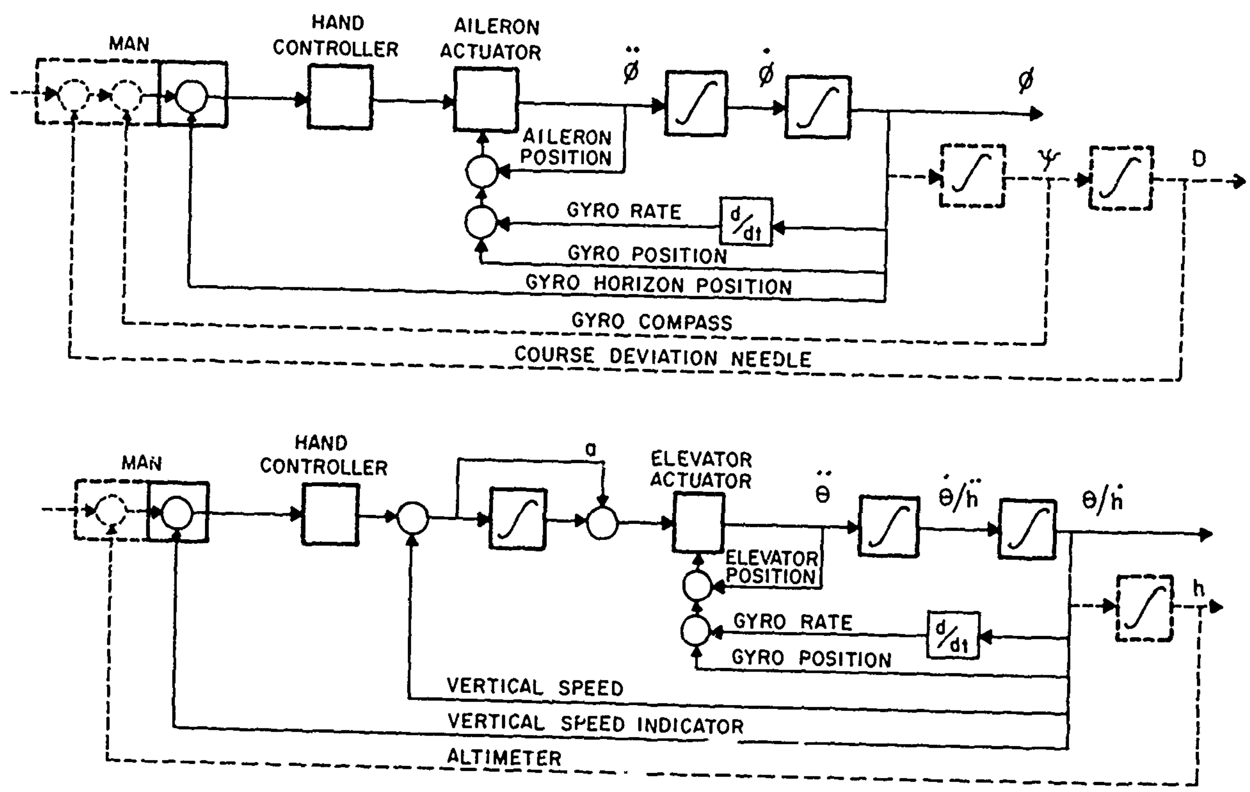

Figure 5. The PCS model.

When the automatically controlled variables, such as bank angle and vertical speed, are those with which the pilot is immediately concerned, the pilot operates as a zero-order controller. But when course deviation and altitude become the controlled variables, as shown by dashed lines, bank angle and vertical speed must be varied, and the pilot operates, respectively, as a second-order and a first-order controller in the two dimensions.

Experiments conducted in the GAT-2 required pilots to perform complex procedures associated with computer-assisted area navigation. A second group of pilots was required to fly and navigate the simulated airplane and, concurrently, to perform an automatically adaptive digit-cancelling side task. Cockpit procedural errors were reduced by a factor of ten when using the PCS, as illustrated in Figure 6. Errors in course following and altitude control made by pilots using the performance control system (PCS) were also reduced sharply, as shown in Figure 7 and 8, respectively. Similar results were obtained whether or not pilots were required to perform the side task, although the stress produced by the side-task approximately doubled the overall frequency of each type of error. With computer storage of either 4 or 8 waypoints, the eight pilots who flew without the side task made no procedural errors during a total of 16 flights.

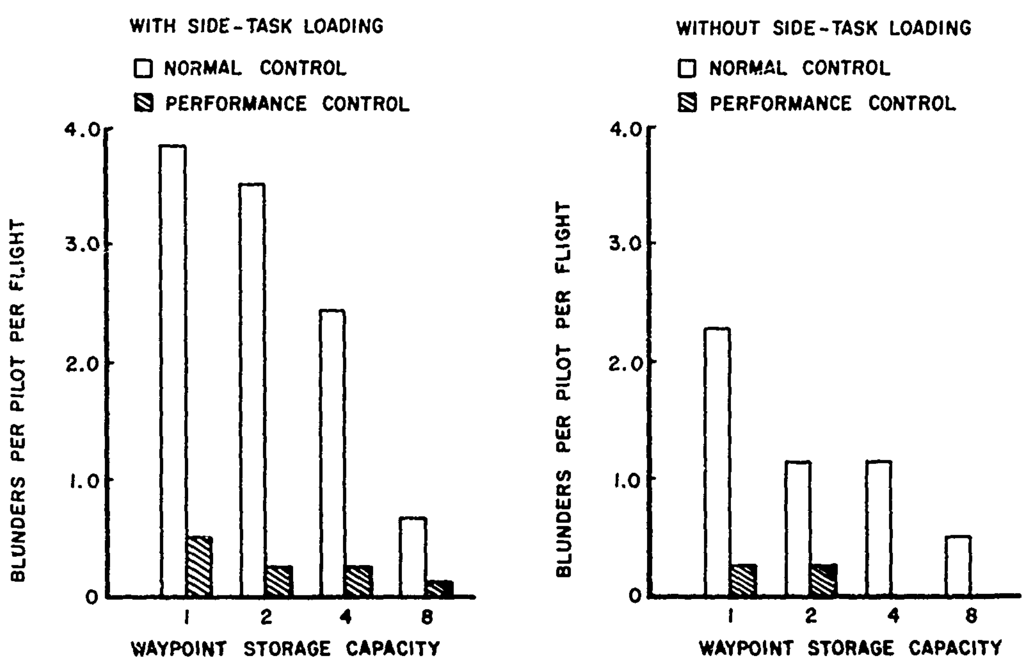

Figure 6. Area navigation procedural blunders as a function of computer waypoint storage capacity for normal control and flight performance control, with and without side-task loading.

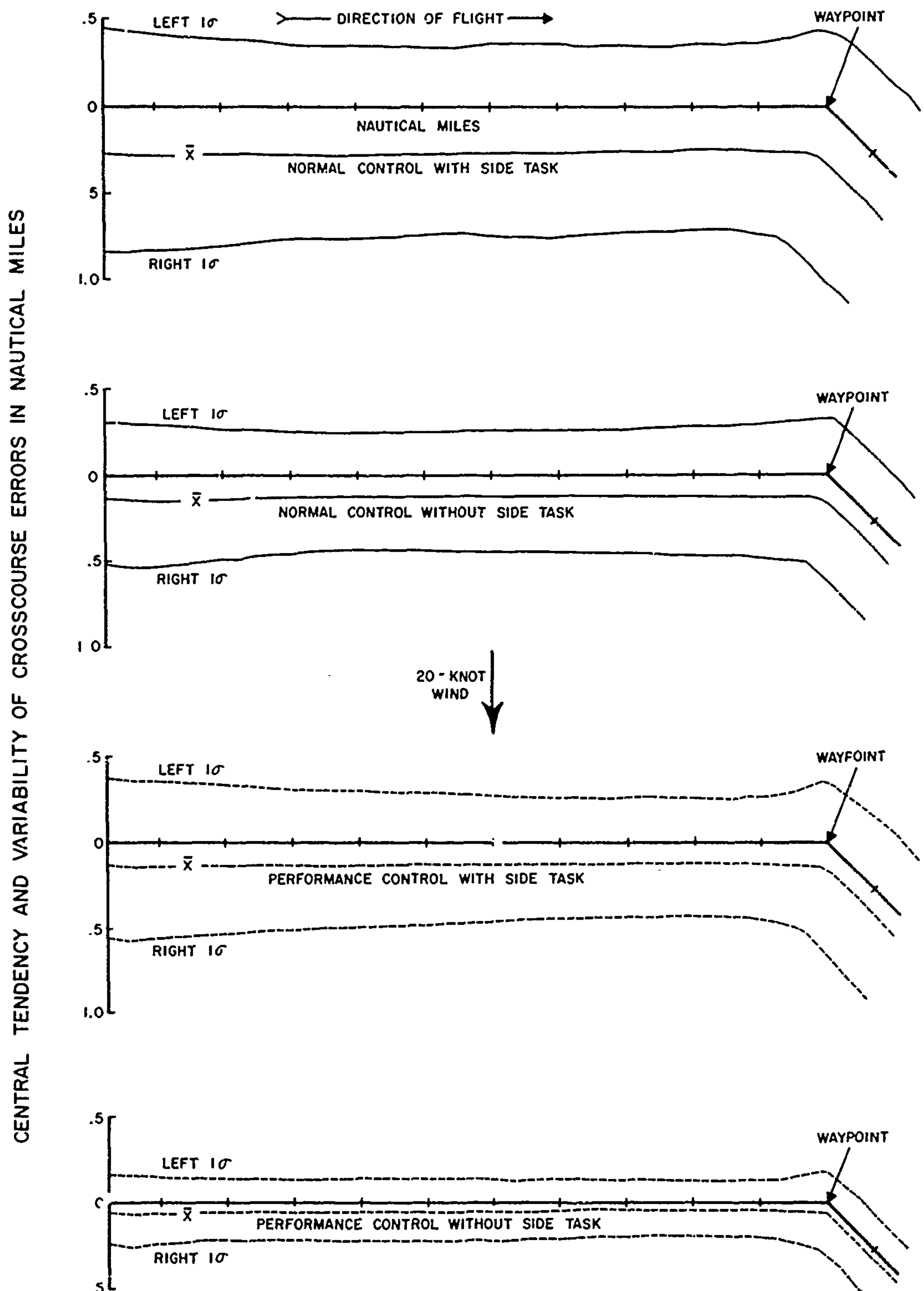

Figure 7. Central tendency and variability of crosscourse error with normal control and performance control as a function of distance from waypoint averaged for eight route segments of 12 nmi each.

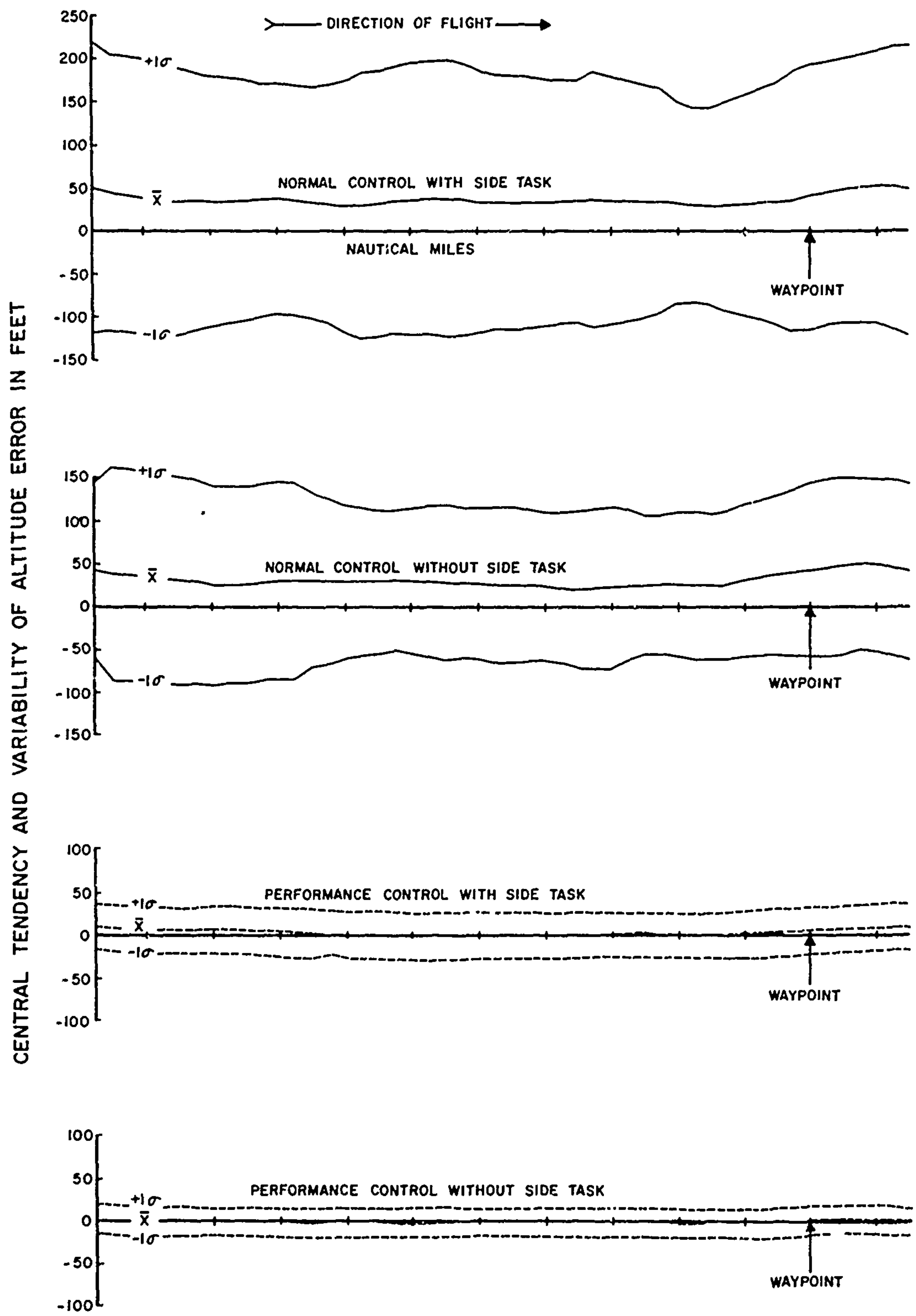

Figure 8. Central tendency and variability of altitude error with normal control and performance control as a function of distance from waypoint averaged for eight route segments of 12 nmi each.

For the pilots who performed the digit-cancelling side task while flying and navigating, residual attention levels indicated by side-task scores closely paralleled the improvements in primary-task performances associated with the PCS and increasing computer storage of waypoints. By inference, the reallocation of a portion of the pilot's former continuous control, memory, and procedural functions to the computer reduced cockpit workload demands and improved system performance without depriving him of essential authority, as indicated by the flight control performances reflected in Figures 7 and 8.

Incidental to the evaluation of the performance control system, but nonetheless showing the importance of proper function allocation, were the findings concerning the preflight storage of navigation information in the airborne computer rather than requiring the pilot to enter way-point positions enroute. Clearly, the emergence of reliable, low-cost airborne computing technology allows the design engineer to unburden the flight crew, not only of routine manipulations but also of short-term memory and procedural requirements with a consequent reduction in blunders and an increase in residual attention for uniquely human functions.

With a flight-qualified PCS in a Beechcraft Twin Bonanza airplane, Bergman (1975) explored a wider range of flight tasks than were included in the Kraus studies. Performances in flight with the PCS were again superior to those with normal aircraft control, but problems not observed in the simulator studies were encountered in flight, particularly in sustained climbs and descents which required continuous force applications by the pilot. Solutions to this and an assortment of minor technical problems recommended by Bergman, as well as provisions for smooth transitional control from one aircraft configuration to another, have been implemented in the Link GAT-2 simulator by Daly, as described in Appendix A.

It is becoming evident that eliminating conventional control inconsistencies and establishing more direct relationships between the pilot's manual control inputs and the response of the aircraft, without depriving him of authority over any useful maneuver, simplifies flight control and thereby allows the pilot to devote more attention to other tasks, as demonstrated by a highly reliable increase in residual pilot attention found in the CCV simulator experiment by Kraus and illustrated in Figure 9.

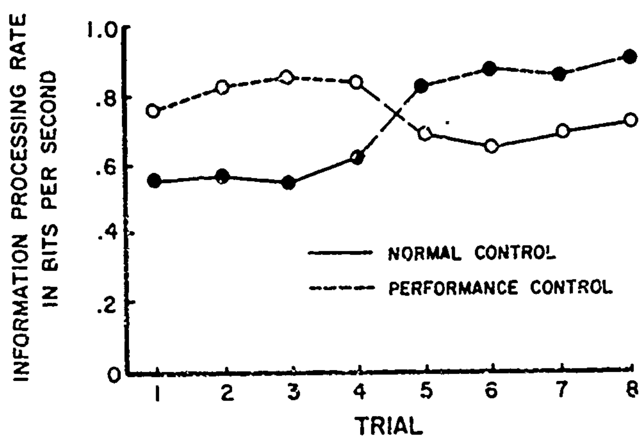

Figure 9. Side-task information processing rates with normal flight control and flight performance control as a function of practice. Faint dashed lines connect performances of subgroups of four pilots each.

The PCS studied in these experiments is functionally similar to the "control wheel steering" of modern transport aircraft through their autopilot systems but allows the pilot to retain a higher degree of control authority and consequently greater aircraft maneuverability. Similar systems for helicopter performance control have been developed and tested experimentally with correspondingly favorable results.

SYNTHETIC PICTORIAL DISPLAYS

An integrated information system should be capable of generating three basic display modes: parametric, graphic, and interactive (McMahan, 1972). Parametric displays dominate the current aircraft cockpit, presenting status indications of vital system and flight variables, such as fuel level, engine performance, and radio frequencies, as well as airspeed, altitude, attitude, and heading. Graphic displays facilitate spatial and geographic orientation, thereby providing aid in navigation, flying traffic patterns, landing the aircraft, and performing any ground-referenced or horizon-referenced maneuver. Interactive displays allow the pilot to communicate with the computer for preflighting, troubleshooting, flight planning, and managing various aircraft systems.

Even though current engineering technology renders computer-generated displays and computer-augmented controls state-of-the-art, research is needed to investigate the man-computer-display and man-computer-control interfaces. Questions such as the information to be displayed, the presentation mode including consideration of the degree of pictorial realism, the essential visual cues for ground-referenced flight, display scale factors and visual angles, and the specific problems associated with IFR to VFR transition procedures must be addressed experimentally.

Questions concerning flight displays cannot be answered completely in isolation from their interactive use in conjunction with flight controls. The application of computer-augmentation to eliminate inconsistencies of flight response dynamics involves a delicate process of display "impedance matching" if the pilot's workload is to be reduced without creating new problems.

Display Classification

To understand the complexity of designing an integrated computer-generated display system, a knowledge of types of displays, modes of information coding, and methods of display presentation is fundamental. Electronic sensor-generated and computer-generated displays, intended both for orientation and for guidance and control, may be classified in many ways. Three particularly useful bases for classification are: first, the point of view presented, that is, the spatial reference coordinates of the display; second, the mode of information coding, ranging from the presentation of literal images of the visual scene through full-bodied and skeletal analog representations to the abstract presentation of discrete alphanumeric or digitally symbolic indications; and third, the manner in which they are viewed, whether head-up or head-down and the associated methods of presentation.

Point of view. If the display surface represents a projection of the aircraft's situation upon an imaginary vertical plane ahead of the aircraft, it is called a forward-looking vertical situation display. When the display represents a projection of the aircraft's situation upon a horizontal plane beneath the aircraft, it is termed a downward-looking horizontal situation display. A projection onto a vertical plane parallel to the aircraft's flight path is known as a sideways-looking flight profile display.

In a vertical situation display, or VSD, the basic dimensions are azimuth and elevation. Lateral displacement or translation of display elements signifies change in aircraft heading or horizontal flight path.

Vertical translation of display elements represents change in pitch or vertical flight path. Rotation of display elements denotes movement of the aircraft about the roll axis. Examples of VSDs are flight periscopes, as illustrated in Figure 10, forward-looking infrared scopes, closed-loop TV systems, contact analog displays, and by stretching the definition, some flight director displays.

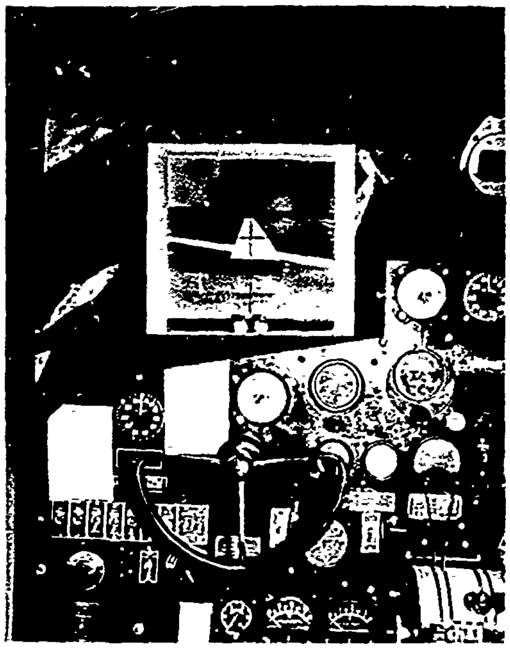

Figure 10. Projection periscope installed through an aluminum windshield in a Cessna T-50 airplane.

A horizontal situation display, or HSD, represents the aircraft's flight path as seen from above looking down on a horizontal plane, such as the ground. The frame of reference of the HSD may be cartesian coordinates as in road maps, azimuth and range coordinates as in plan position (PPI) radar scopes, or a polar grid system as necessitated at high latitudes. HSDs are exemplified by map displays for navigation, as illustrated in Figure 11, and by radar ground maps.

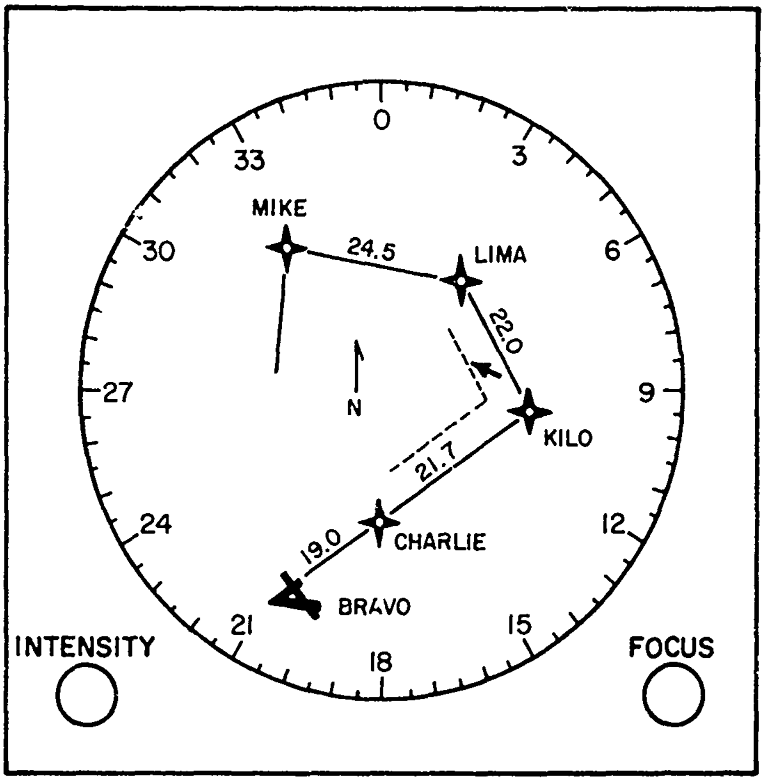

Figure 11. A computer-generated map display showing aircraft position relative to a five-mile left offset from a Standard Instrument Departure route.

Sideways-looking displays have the basic dimensions of elevation or altitude versus range or speed. Displays with this point of view are useful for energy management, maneuvering near the limits of the flight performance envelope, terrain following, and possibly for nap-of-the-earth flight in helicopters. Figure 12 illustrates a sideways-looking display of an airplane capturing a glidescope with the assistance of a vertical flight path trajectory predictor and the comfort of a performance tolerance envelope. In all such displays, both computed guidance commands and projections of the flight path based on fast-time model predictions may be presented, either in proper geometric perspective or by symbolic coding schemes.

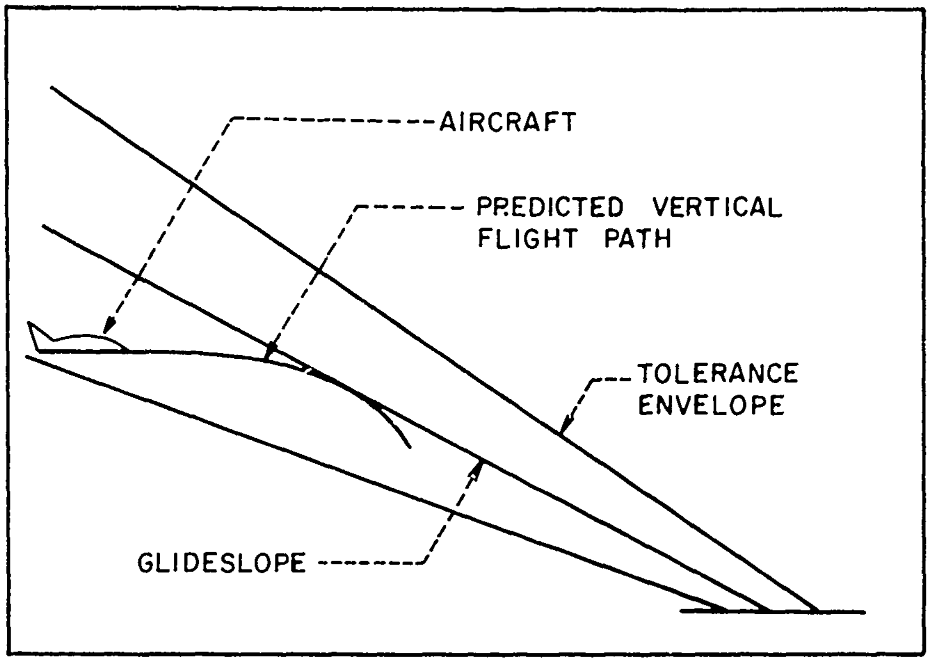

Figure 12. A sideways-looking flight profile display.

Mode of information coding. Flight displays may be classified along a continuum ranging from literal to abstract. Imaging displays range from direct, literal, optical projections, as in the periscope shown in Figure 10, through electronically scanned TV, infrared, and radar pictures, frequently scan-converted, to fully synthetic computer-generated visual scenes analagous to animated cartoons drawn in real time. Visual systems commonly used in modern flight simulators project dynamic, perspective, color TV images of realistically scaled models of airports to represent contact landing scenes as viewed from the cockpit. Closed-loop low-light TV and infrared sensors can present similar dynamic images on panel-mounted or helmet-mounted displays within the cockpit.

Computer-generated imaging displays are on the threshold of widespread use in presenting dynamic pictorial scenes analagous to the pilot's contact view, initially in visual systems for flight simulators and soon thereafter in airborne cockpit displays. Advocates of computer-generated imaging displays implicitly have assumed that all information essential to the pilot for ground-referenced maneuvers, such as takeoff and landing, terrain following, weapon delivery, and air combat, is available from a clear view of the outside world. A great deal of effort on these "contact analog" displays has been directed toward generating realistic dynamic images of airports and their surrounding terrain and topography.

A more fundamental approach is to isolate the essential visual cues from the contact view that the pilot uses in landing the aircraft and in other ground-referenced operations and incorporate them into a display that may present a highly stylized contact view in which the dynamic responses of the pictured elements are analagous to those of their visual-world counterparts in contact flight. A contact analog is not a camera image of the real-world scene; it is a wholly artificial recreation of essential real-world visual cues. A true contact analog display, however abstract or "skeletal" it may become, remains pictorial in that all elements obey the same laws of motion perspective as their visual-world counterparts.

Horizontal situation displays and flight profile displays retain certain pictorial properties, but they typically differ from VSDs in the direction of relatively greater abstraction. Computer-generated map displays, in particular, present a skeletal appearance, and performance envelope displays are not only skeletal in appearance but may incorporate intentional scale distortions. The ultimate level of abstraction is represented by alphanumeric readouts, discrete warning indicators, and other symbolic displays that retain no pictorial properties whatever.

Method of presentation. Displays can also be classified according to how they are viewed. Direct-view displays, such as those created on CRTs, storage tubes, and plasma panels present information directly to the observer on the surface of the image-producing display medium. When the image is generated on a device out of the direct view of the observer, then projected by an optical system to a location in the observer's head-up view, the observer sees a virtual-image display. Virtual-image displays are exemplified by collimated light images projected onto a combining glass or windshield in front of the pilot. This type of display is called a head-up display, or HUD (Gold and Walchli, 1974; Naish, undated; Baxter and Workman, 1962).

There has been a long standing, often emotional debate over the relative merits of head-up projected displays and head-down direct-view displays and a more recent debate as to the relative merits of helmet-mounted CRT presentations. Each has its superficially apparent advantages for application to specific flight operations.

Proponents of head-up presentation place great importance on the superpositioning of collimated guidance and control information on the outside visual scene, ostensibly to minimize shifts in eye fixation and accommodation during critical flight phases. However, head-up displays have been applied effectively only to landing and military weapon delivery because of the technical problems associated with their limited fields of view, restriction of pilot head movements, inflexibility of scale factors, misregistration of projected symbols with their real-world referents, and the associated penalties in size, weight, and cost.

Proponents of collimated sensor-generated and computer-generated displays projected from small helmet-mounted CRTs (1-in diameter or less) onto the pilot's helmet visor, or other integral combining glass, emphasize the advantages of free head movements, somewhat greater fields of view, variable scale factors in certain applications, accuracy of registration between computer-generated symbology and sensor-generated imagery, and the associated savings in size, weight, and cost. But helmet-mounted displays present problems in maintaining image visibility through wide ranges of ambient illumination and contrast, rivalry and misregistration between projected and real-world scenes, and despite recent major improvements in weight, balance, and integral packaging, some pilot discomfort and restriction of movement.

Pictorial Vertical Situation Displays

Carel (1965) defines a pictorial display as one meeting two criteria. First, there is a geometric similarity between the elements in the display and the structure of the contact visual environment. Second, the motion of the displayed elements is similar to that of their real world correlates. The literal and skeletal analog displays defined previously may all be called pictorial displays, differing only in the amount of visual realism portrayed. Each has been proposed for flight application to ground-referenced maneuvers.

Literal VSDs. The most literal displays for landing are periscope displays. Roscoe, *et al*., conducted several studies using a projection periscope mounted in a Cessna T-50. The pilot saw the forward view on an 8-in ground glass screen mounted above the instrument panel with the periscope projecting through an aluminum windshield. Although safe takeoffs and landings were made by periscope under all experimental conditions studied, the accuracy of landings both in terms of constant and variable errors was significantly influenced by the image magnification employed, the optimum value being about 1.25. Campbell, McEachern, and Marg (1955) used a binocular periscope to investigate pilot performance during approach and landing and reached the same conclusions.

Bell Helicopter Company developed a closed-loop TV system for use on a helicopter (Elam, 1964). The TV camera was mounted either on the skids or at eye level and could be slewed or held stationary. Results of their investigation showed that for takeoff there was no appreciable difference between performance using the TV and performance with direct contact visibility, but for landing there was an appreciable difference. Using the TV, the pilots tended to "sneak up" on the landing pad and then feel their way down, because if a large flare were used, the ground would disappear. The authors concluded that the helicopter could be landed within an acceptable touchdown area using a closed-loop TV system if conditions were highly favorable with no crosswind or obstacles in the approach path.

Kibort and Drinkwater (1964) tested the effectiveness of a TV display in a DC-3 airplane for the final approach and landing. A slewable camera was mounted on the nose, and a second camera was placed just forward of the tail wheel. The output of either camera could be fed to a 14-in monitor that was viewed somewhat obliquely to subtend 16 to 17 deg at the pilot's eye. Pilots flew 3 deg approaches from 3 mi out, through touchdown and rollout. Kibort and Drinkwater concluded that the pilot needs only quantitative airspeed information when flying VFR but quantitative airspeed, rate of climb, and altitude information with the TV display. They found that display magnification is desirable because it results in increased "display gain."

From the meager evidence available, an unaided, literal, TV or infrared vertical raster-scan display used as the primary instrument for landing appears inadequate, despite the favorable results obtained in periscope studies. However, if guidance information for navigation and flight maneuver control is added to any literal display, the display's scenic detail would appear to support the pilot's spatial and geographic orientation and serve as an independent monitor of the reasonableness of the flight situation. Information presented by a literal display is believable, landmarks are available for navigation, and the pilot may confidently choose among alternative courses of action. A literal display also takes advantage of the ingrained perceptual habits that pilots acquire from VFR flight.

Analog VSDs. Carel (1965) defines the contact analog display as "the point perspective projection of a three-dimensional model to a picture plane," as illustrated in Figure 13. A computer-generated model contains reference objects significant for flight performance such as a surface representing the horizon and the ground plane, a surface representing the command path for the pilot to follow, sometimes called a "highway in the sky," and other surfaces or objects useful during various phases of a mission.

> Most importantly, the displayed surface dynamics are similar to those of their analog surfaces in the natural visual environment. The displayed surfaces still follow the laws of motion perspective, thus providing information coded in a fashion analagous to the coding provided in visual contact flight.

Investigators at Bell Helicopter Company carried out simulator and flight tests using a Norden contact analog display. Emery and Dougherty (1964) had pilots perform various maneuvers in the Bell moving-base simulator. The content of the displays was varied in four test conditions: ground plane only, ground plane and landing pad, ground plane with flight path border, and ground plane with flight path border and black "tarstrips"

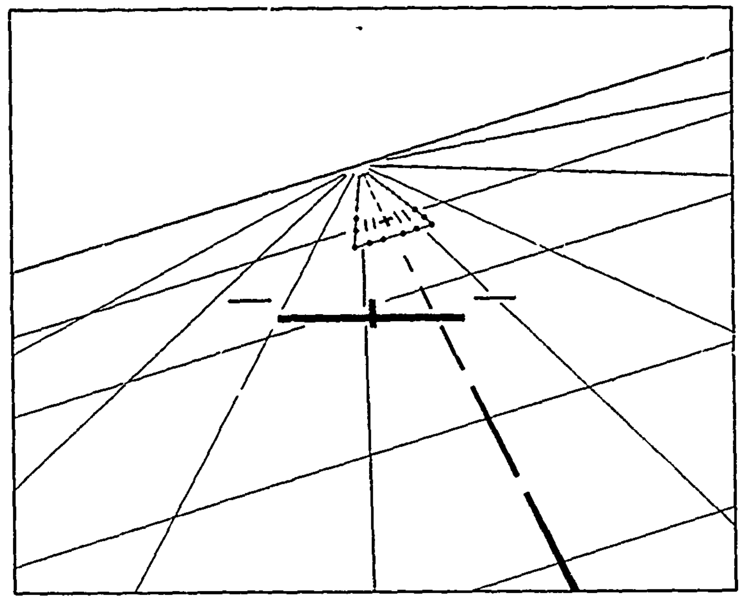

Figure 13. A skeletal contact analog.

perpendicular to the border edges. Results showed that as command guidance information was added, performance improved, pilots doing better with the flight path than without.

Dougherty, Emery, and Curtin (1964) compared performance using the same contact analog display to performance using standard instrumentation. Two groups were trained to a criterion of "performance equivalence" using either of the two display systems, in a moving-base helicopter simulator. The task was to hold command altitude, heading, course, and airspeed while concurrently performing a digit-reading side task that required a variable reading rate. The side task, as a measure of workload, was used to indicate which display would allow more time for a secondary task before the primary task suffered a performance decrement. Results indicated little difference in performance using either display system when the pilot was not stressed with the side task. However, with the contact analog performance remained relatively stable with the elevated workload whereas performance with standard instruments deteriorated.

From these results Dougherty, et al. (1964) concluded that information can be assimilated more rapidly with the contact analog pictorial display and attributed this to three factors:

1. The pilot may more quickly assimilate qualitative information from the pictorial display.

2. Using conventional information the pilot samples one parameter of information per glance. With the pictorial display he accumulates information on more than one parameter per glance.

3. Because of its relatively large angular field of view, the pictorial display permits use of peripheral vision.

Cross and Cavallero (1971) investigated pilot performance during simulated landing approaches to an aircraft carrier using a contact analog display at the Naval Missile Center, Pt. Mugu. Performances in the simulator were found to be "comparable" to performances on approaches in an actual F-4 aircraft to a CVA carrier. In addition, pilot opinions were that the nature and level of task difficulty experienced in the simulator were similar to the conditions encountered in the actual aircraft in the landing phase. From the evidence, synthetically generated contact analog displays appear to facilitate spatial orientation and allow manual control not greatly different from literal imaging displays of comparable dimensions.

Skeletal VSDs retain the dynamic pictorial properties of full-bodied contact analogs, but their elements are not intended as "look alike" analog representations of real-world objects. In skeletal VSDs, the way symbols move and their relationships to one another are geometrically faithful to the dynamics of their visual-world counterparts. However, the criteria for the choice of symbology are merely that symbols be clearly discernable and discriminable from one another, and readily identified with their referents. HUDs typically represent the extreme in skeletal abstraction, and most of the research on skeletal analog representation has involved this type of display. Unfortunately, little of a generalizable nature can be concluded from it.

DISPLAY-CONTROL SYNTHESIS

The functions performed by any given airplane and its information-processing subsystems are highly mission dependent, and the missions airplanes are called upon to perform change both as a function of our galloping aeronautical technology and the Yankee ingenuity of our flight crews. Despite extensive predesign mission and task analyses, airplane designers accept with resignation the fact that pilots will invent previously unheard of things to do with their airplanes, and other engineers will respond quickly with previously unimagined add-on devices to help the pilots do them. The consequence is a cockpit patchwork that grows in confusion throughout each airplane's life cycle while retaining vestiges of confusion from earlier cockpits.

The serial consequences include increased logistic and maintenance demands, increased pilot training requirements and difficulty for experienced pilots both in transitioning to new airplanes and in transferring from one old airplane to another, and perennially renewed clamor for cockpit standardization. Engineering test pilots frequently acknowledge that cockpit standardization is a good idea but hasten to point out that right now is not a good time to do it because things are changing so rapidly at the moment. It always seems to be too early or too late to start with a clean instrument panel and synthesize a context within which new mission requirements may be readily accommodated.

In a sense it was too early, prior to this decade, to undertake the synthesis of a universal system that could accommodate new requirements through software rather than hardware changes without introducing new coordinate systems or incompatible information codes and control-display relations. Computing and display technology now supports such an undertaking as a low-risk venture. Within two large electronically scan-converted displays could be synthesized essential orientation, guidance, prediction, control, and independent flight monitoring information for any mission function from the forward-looking and downward-looking points of view. Two somewhat smaller displays might be dedicated to speed and altitude information, including their derivatives and associated commands and predictions, and a final multipurpose display might mediate energy management, preflight and inflight system testing and monitoring, communication management, and assorted housekeeping.

A gross sketch of such a cockpit configuration is ventured in Figure 14. Each of the large displays should be thought of as an interactive electronic chalkboard on which both the computer and the pilot can write. Both the forward-looking and downward-looking chalkboards would accurately register dynamic real-time sensor-generated imagery within the skeletal context of the computer-generated forward-looking scene or the downward-looking map, thereby accommodating specialized military requirements. A minimum of dedicated single-parameter standby instruments would be retained initially, for whatever comfort they may afford, and a clock. Flight performance control would be provided through interlocked dual side-arm controllers, thereby allowing the pilot to fly with either hand comfortably and eliminating the visual obstruction created by a central stick or yoke.

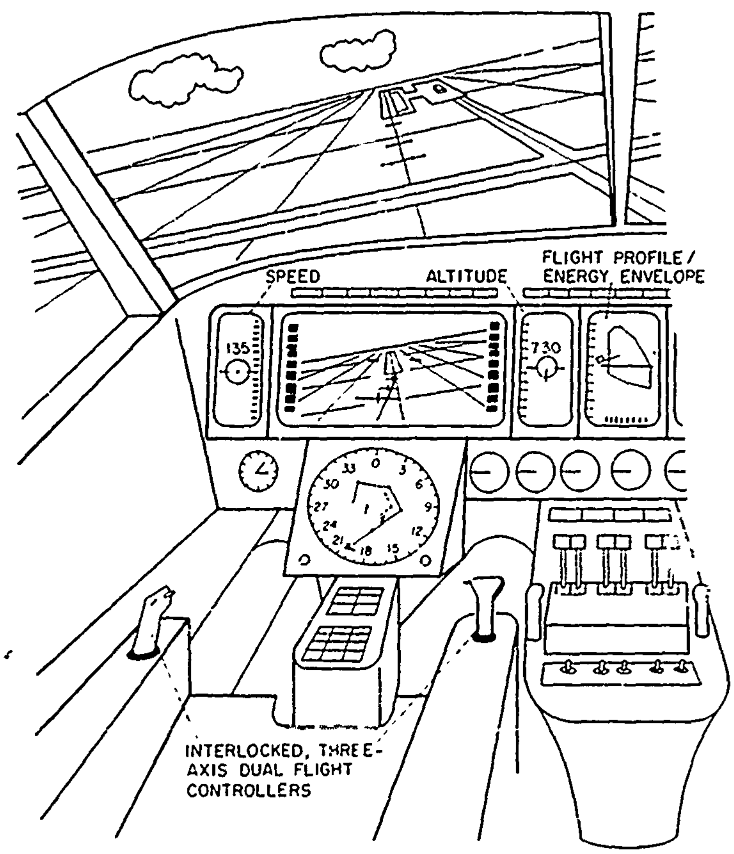

Figure 14. Reconfigured airplane cockpit illustrating future arrangement of integrated computer-generated displays and computer-augmented controls.

The computer-generated forward-looking scene, shown by itself in Figure 15, would be quite skeletal, to accommodate the superpositioning of dynamic forward-looking infrared or low-light TV imagery without serious rivalry. Both command guidance and a frequency-separated projection of the predicted flight path, as shown by the successively smaller airplane symbols in Figure 15, would be superposed in true perspective upon the computer-generated scene. As shown, the airplane is low and to the left of a normal straight in approach and banked to the right,

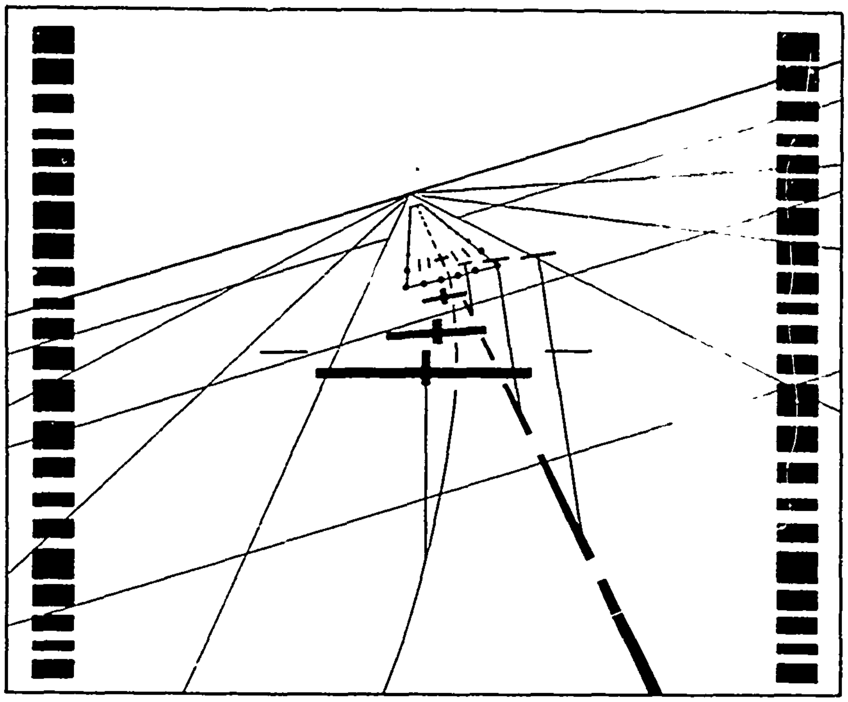

Figure 15. Computer-generated contact analog display with fast-time predictive flight-path projection and speed-error and vertical-error rate fields at left and right, respectively.

but the pilot has made the proper control input to pull up and roll left to bring the airplane to the desired touchdown point.

Command guidance may be introduced selectively and presented in ways that create a minimum of clutter to obscure the basically pictorial presentation. The prominent vertical rate fields to the left and right may be used to present speed and vertical flight path guidance. By nulling the rate-field motion, the pilot nulls the errors relative to the computed desired values of the moment. In mission phases other than the landing approach depicted, the rate fields might present command guidance for speed and altitude control in 4-D navigation, inflight refueling, or other operations requiring precise flight control.

By bringing the outside world into the cockpit through the superpositioning of dynamic imagery from high-resolution sensors with limited weather penetrating capabilities, the head-up/head-down controversy would be resolved in favor of the latter for all flight operations other than vestigial contact maneuvers (even air combat might be performed more effectively head-down with modern sensing, computing, and display capabilities). Problems historically associated with IFR to VFR transition would dissolve since, in effect, there would be none in the traditional sense. Truly all-weather (Category III) operation includes conditions in which the pilot has no contact visibility even while taxiing. In such conditions it is common for airport vehicles as well as airplanes to become lost, and the flight crew must determine not only that the airplane will land on the runway but also that the runway, or taxiway, is otherwise unoccupied.

Because Category III weather occurs extremely infrequently, the pilot's ability to cope with it will require either supplemental training under simulated Category III conditions or routine operation as if such conditions were present all the time -- or perhaps a combination of both. Despite the fact that automatically coupled landing approaches are made routinely in transport aircraft, and thousands of fully automatic landings have been made safely, there is still a legal requirement to see the runway at or above some "decision height" (for precision approaches) or "minimum descent altitude" (for nonprecision approaches) before allowing the airplane to land.

In Category III operations, this "see to land" requirement, by definition, will be eliminated and replaced by a requirement for a weather-penetrating sensor system that will provide an alternate means of "seeing to land" or otherwise guaranteeing that it is safe to do so. Because low-visibility landing accidents are most frequently attributed to the required visual transition between instrument indications and the runway surface or its lighting configuration at a critical moment, many believe that "being able to see a little bit" creates problems that will not be present when the required visual transition is eliminated. If a true all-weather landing display were used in good weather as well as bad, Category III operations should be safer than Category II operations are today.

The quarter-century-old concept of total flight capability entirely by instrument reference, limited only by aircraft performance and human tolerance, is rapidly approaching technological feasibility. As observed by Williams in 1947, the problem is still "to break away from the notion of specific ways for presenting information ... [and] to develop a scheme into which all pieces of information will fit in a logical way." The digital transformation of sensor-derived information, including real-time literal imagery, for integral presentation with stored geographic, topographic, and aerodynamic information is now technically as well as logically feasible.

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

CDR James Goodson
Chief, Aerospace Psychology Division
Naval Aerospace Medical Institute
Pensacola, FL 32512

Bureau of Naval Personnel
Special Assistant for Research Liaison
PERS-OR
Washington, DC 20370

Dr. Fred Muckler
Manned Systems Design, Code 311
Navy Personnel Research and
Development Center
San Diego, CA 92152

CDR Robert Wherry
Human Factors Engineering Branch
Crew Systems Department
Naval Air Development Center
Johnsville
Warminster, PA 18974

CDR Robert Kennedy
Human Factors Engineering Branch
Code 5342
Pacific Missile Test Center
Point Mugu, CA 93042

Mr. Ronald A. Erickson
Head, Human Factors Branch,
Code 4075
Naval Weapons Center
China Lake, CA 93555

Systems Engineering Test
Directorate
ATTN: Mr. F. Hoerner
U. S. Naval Air Test Center
Patuxent River, MD 20670

Mr. Richard Coburn
Head, Human Factors Division
Naval Electornics Laboratory Center
San Diego, CA 92152

Mr. James L. Long
Weapons Systems Research (N-332)
Naval Education & Training Command
Naval Air Station
Pensacola, FL 32508

Human Factors Dept., Code N215
Naval Training Equipment Center
Orlando, FL 32813

Dr. Alfred F. Smode
Training Analysis & Evaluation Group
Naval Training Equipment Center
Code N-00T
Orlando, FL 32813

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

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

U.S. Air Force Office of
Scientific Research
Life Sciences Directorate, NL
1400 Wilson Boulevard
Arlington, VA 22209

Chief, Human Engineering Division
Aerospace Medical Research Lab
Wright-Patterson AFB, OH 45433

Lt. Col. Joseph A. Birt
Human Engineering Division
Aerospace Medical Research Laboratory
Wright Patterson, AFB, OH 45433

Dr. Stanley Deutsch
Office of Life Sciences
Headquarters, NASA
600 Independence Avenue
Washington, DC 20546

Dr. Clyde Brictson
Dunlap and Associates, Inc.
115 South Oak Street
Inglewood, CA 90301

Mr. Edward Connelly
OMNEMII, Inc.
Tyson's International Bldg.
8150 Leesburg Pike, Suite 600
Vienna, VA 22180

Dr. E. Jones, Life Sciences Dept.
McDonnell Douglas Astronautics Co.-East
St. Louis, MO 63166

Mr. Gail J. Borden
Human Factors Research, Inc.
Santa Barbara Research Park
6780 Cortona Drive
Goleta, CA 93017

Dr. Gordon H. Robinson
University of Wisconsin - Madison
Department of Industrial Engineering
1513 University Avenue
Madison, WI 53706

Dr. W. S. Vaughan
Oceanautics, Inc.
3308 Dodge Park Road
Landover, MD 20785

Director, Human Factors Wing
Defense & Civil Institute of
Environmental Medicine
Post Office Box 2000
Downsville, Toronto, Ontario
CANADA