CONCEPTUAL DESIGN OF A ROTORCRAFT ADVANCED VISUAL SYSTEM*

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ABSTRACT

A conceptual design is presented of a large field-of-view, high resolution visual system with an integrated flexible cab configuration that can be procured with a high degree of confidence in the 1982-84 time period. The mission requirements are defined for the Army Rotorcraft System Integration Simulator (RSIS) which incorporates this Advanced Cab and Visual System (ACAVS). A brief description is provided of the NASA-Ames Vertical Motion Simulator as it will be configured with ACAVS installed. Major ACAVS system requirements are addressed and some attention is given to their relationships to the intended mission. Four existing visual display technologies and computer generated imagery approaches are identified and their potential application to ACAVS is described. The ACAVS conceptual design is presented and a comparison is made of major requirements and goals to final system specifications.

The paper closes with a brief discussion of potential applications of the RSIS to future helicopter systems design, integration, product improvement evaluations and safety analysis.

INTRODUCTION

Over the last 20 years, flight simulators have emerged as a recognized and widely accepted training tool. A survey of all 23 scheduled U.S. Airlines revealed that more than 70 modern flight simulators are owned and operated by the 18 airlines who replied to the survey. Currently, a very large part of all commercial airline flight training is conducted in those flight simulators[1].

The use of simulators for training within the Department of Defense (DOD) began during World War II to increase instrument flying proficiency. During the next twenty years, the feasibility of real time digital simulators for flight training was demonstrated. Weapons systems simulators followed with the development of the terrain model board and TV approach for visual simulation. In 1969 Apollo II landed on the moon validating, on the first flight, the effective use of total simulation in the training program[2].

While their value has been widely exploited by the fixed-wing industry for many years, piloted flight simulators have seen much less use by the rotary-wing industry. In 1971, the U.S. Army initiated an extensive program in the use of simulators for training helicopter aircrews with its introduction of the UH-1H Synthetic Flight Training System. Since then training simulators have been developed for the CH-47 Chinook and AH-1 Cobra, and one is undergoing acceptance testing for the UH-60A Blackhawk. Similarly, the U.S. Navy introduced a Weapons System Trainer for the SH-2F Seasprite in 1976 and have systems under development for the CH-46E Sea Knight and SH-3H Sea King[3].

In the fixed-wing aircraft industry the cost-effectiveness of piloted flight simulators has also been demonstrated in research and development[4]. It has become a primary tool in the understanding of the flight characteristics of new aircraft, the development of certification criteria, the validation of aircraft control concepts, and the formulation of new approaches to air traffic control procedures.

In contrast, there has been limited exploitation of man-in-the-loop simulation during the research and development phases of rotary-wing aircraft. Some examples are the use of Northrop's capabilities during development of the Heavy Lift Helicopter, simulations performed by Sikorsky and NASA-Langley in support of the tilt rotor development and Stability and Control Augmentation System (SCAS) failure investigations on the Bell 214.

In 1975, a joint U.S. Army and NASA study was performed to review the functions, status and future needs for ground-based flight simulation of rotary-wing aircraft. Contacts were made with the U.S. helicopter industry and with the various U.S. agencies concerned with the development of rotary-wing systems to assess the needs for research simulation. In the course of this review, the deficiencies in current simulation capability relative to rotary-wing aircraft requirements were defined with consideration of all the special aspects of this problem including mission, tasks, aircraft characteristics, environmental conditions, instrumentation and displays, performance and workload. Many of these aspects impose requirements quite different from those met by even the most sophisticated fixed-wing piloted simulators. As a result of this review[5], a program was initiated to develop a high-fidelity rotorcraft simulation capability that could be exploited by both government and industry in Research and Development (R&D). This simulation capability is being developed jointly by the Aeromechanics Laboratory and NASA at NASA-Ames Research Center, Moffett Field, California. The Aeromechanics Laboratory is one of four research laboratories assigned to the Research and Technology Laboratories (RTL) of the U.S. Army Aviation Research and Development Command (AVRADCOM).

Research Simulator Requirements

There are many differences between fixed-wing aircraft and rotary-wing aircraft that imply different simulation requirements. Generally, fixed-wing aircraft fly high and relatively fast and are close to the ground only when landing or when taking off. In contrast, helicopters fly low and slow and, especially during military missions, are in close proximity to the ground during most of their flying time. The term Nap-of-the-Earth (NOE) (Figure 1) has been coined by the

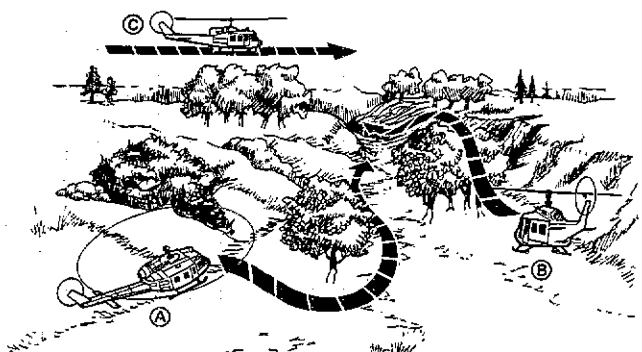

Figure 1. Terrain Flying Regimes

*Much of the information presented in this paper was developed on NASA Contract NAS2-10464, NASA-Ames Research Center, Moffet Field, CA.

helicopter community to describe operations in which they fly only a few feet above the ground and fly around obstacles rather than over them. The environment for the pilots flying these missions is rich in detail – full of trees and bushes, hills, and valleys, which, while offering protection from the enemy, are lethal to an unwary pilot. Terrain features, visibility factors of weather and darkness, and atmospheric characteristics of wind, turbulence, and ground effect are all elements of the environment that may significantly affect the helicopter pilot's tasks. The helicopter crew must maneuver around and between obstacles and navigate, communicate, and proceed with the mission while maintaining awareness of threat weapons.

Fundamental differences in the environmental cues which have to be simulated for rotorcraft operations compared with fixed-wing aircraft result from these different flight conditions. The visual display is required to represent much more detail in the terrain and vegetation. Being close to the ground, terrain, and vegetation characteristics cause more complex atmospheric wind shear and turbulence characteristics. Slow flight speed and, in particular, the conditions in and around hover make assumptions of a non-time-varying turbulence model invalid, and satisfactory turbulence models more difficult to achieve. Slow flight and high maneuverability, especially of military helicopters, allow rapid changes of flight path to be achieved. This means that the field of view required for the pilot to see where he is going is wider than in a fixed-wing aircraft.

The basic control problems are more difficult too. In a fixed-wing aircraft with good handling qualities, the aircraft is stable, and control is largely a two-axis task with pitch and bank angles being used to direct the aircraft flight path. In a helicopter, especially at speeds approaching hover, pitch attitude becomes less effective in controlling flight path angles and more effective in controlling of speed, while an additional control, thrust, is required for rate of climb. In addition, heading is no longer controlled by bank angle but also requires an additional specific control through the yaw control. Thus, the pilot's control problem becomes much more complex; it now requires all four controls to be actively worked. In addition to this fundamental control problem, the basic helicopter is likely to be unstable and to have significant cross coupling between the various axes. All these complications associated with helicopters make the need for the additional cues provided by a simulator motion system greater than in the case of fixed-wing aircraft.

Finally, the mathematical model required for a reasonable representation of a helicopter must contain some elements of rotor dynamics, the extent depending on the purpose and nature of the simulation. Thus, the requirements on the visual, motion, and computational aspects are all different, and generally significantly more severe than those for a simulation of similar fidelity for a fixed-wing aircraft.

Project Plan

The joint Army/NASA program to develop a high-fidelity R&D simulator, known as the Rotorcraft System Integration Simulator (RSIS), is now in its final phase. The first, or definition phase, started with the Army/NASA study in 1975[5], which led to additional studies to address the issues raised by the different requirements discussed previously for rotorcraft R&D simulation as opposed to fixed wing simulation. A feasibility study for helicopter/VTOL wide-angle simulator image generation displays system was completed by Northrop in 1977[6]. Results showed that wide field of view visual display (120°H x 60°V) was feasible using the techniques of image generation by camera model and image-presentation by three color projectors. The image presentation technique is still a possible candidate but the limited resolution and inability to expand the field of view suggest that Computer Generated Imagery (CGI) may be a better solution for image generation. Analysis of fixed-based simulations of NOE flight operations[7], has defined the cab excursions required for high fidelity simulation motion. Due to budgetary constraints and a desire to make maximum use of existing facilities, it was determined that the Vertical Motion Simulator (VMS) at NASA-Ames could be used, with modifications at the motion base for the RSIS. The VMS will be described in more detail later in this report. Two independent design studies to assess the possible modification were performed by Franklin Research Laboratory and Northrop Corporation in 1978[8][9]. Specifications were developed from these studies and a competitive RFP was issued to industry and the contract was awarded to Franklin Laboratory in 1979.

A new interchangeable rotorcraft cab, a development station, and an advanced visual system, known as the Advanced Cab and Visual Systems (ACAVS) will complete the RSIS project. The development station and interchangeable rotorcraft cab will enable Army/NASA researchers to release the VMS for additional experiments while reconfiguring the cab in the development station for the next rotorcraft experiment. The advanced visual system will be a wide field of view system with look-down capability. An overview of the RSIS project and its relationship with the VMS is shown in Figure 2. The final configuration with all component parts is also shown, conceptually, in Figure 3. The dome concept is shown as a feasible concept only and does not imply that other concepts will not be considered for the advanced visual system.

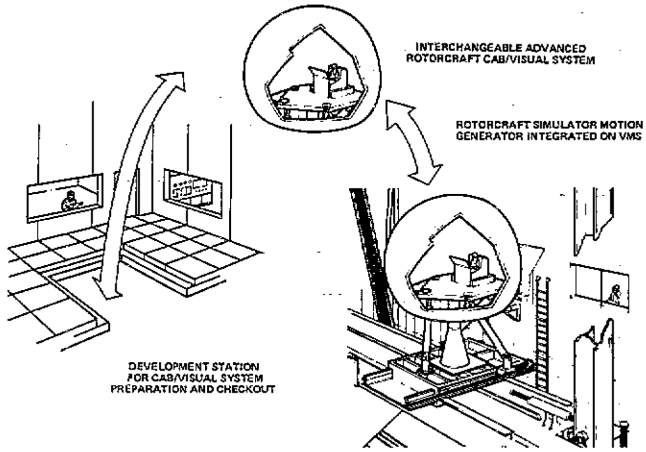

Figure 2. The Vertical Motion Simulator (VMS) RSIS Project Overview

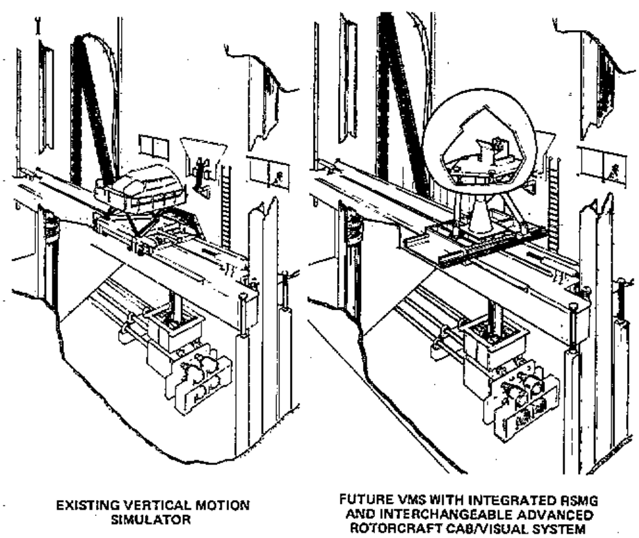

Figure 3. Final RSIS System

To provide an effective review of rapidly advancing technology, especially in the visual area, a preliminary design study contract was awarded to Boeing Military Airplane Company in late 1979. Their finding will be discussed next. A Statement of Work and RFP was developed from their study and is awaiting release to industry. The ACAVS contract will be awarded in 1981 and the RSIS is scheduled to become operational in 1985.

VERTICAL MOTION SIMULATOR DESCRIPTION

The Vertical Motion Simulator (VMS) is a large man-carrying simulator now in operation at Ames Research Center. The VMS consists of a hydraulic motion system mounted on a structure with large lateral and vertical motion capabilities. Vertical motion is the primary degree-of-freedom and all other modes are built on top of it. A long horizontal platform is supported by two vertical columns. Currently eight (8) DC servo-motors drive the simulator sixty feet vertically through gear reducers, pinions, and racks which are attached to the columns. Lateral motion capability of forty feet is provided by a carriage which is driven across the vertical motion platform. Four (4) DC servo-motors drive through reducers and pinions to engage a fixed rack on the vertical motion platform.

As a part of the RSIS program the hydraulic motion system presently mounted on the vertical and lateral structure is being replaced with the Rotorcraft System Motion Generator (RSMG). The overall performance envelope of the combined device is projected to be as follows:

Mode	Displacement	Velocity	Acceleration
Vertical (Z)	± 30 ft.	± 20 ft/sec	± 32.2 ft/sec^2
Lateral (Y)	± 20 ft.	± 10 ft/sec	± 24 ft/sec^2
Longitudinal (X)	± 4 ft.	± 4 ft/sec	± 10 ft/sec^2
Roll	± 78°	± 40°/sec	± 115°/sec^2
Pitch	± 18°	± 40°/sec	± 115°/sec^2
Yaw	± 24°	± 46°/sec	± 115°/sec^2

These peak motion system requirements are defined for a maximum growth payload that includes all hardware attached to the motion system with the following characteristics:

Weight	=	8,000 lbs
Ix-x	=	26,000 in-lb-sec^2
Iy-y	=	31,000 in-lb-sec^2
Iz-z	=	31,000 in-lb-sec^2

ADVANCED VISUAL SYSTEM REQUIREMENTS

The prime projected use of RSIS is handling qualities investigations. In rotorcraft systems, handling qualities depend heavily upon the outside visual scene for most missions. Requirements for ACAVS visual systems stem from the following NASA user-defined simulator mission tasks.

Nap-of-The-Earth Terrain Flight
Night Operations
Instrument Flight
Sling-Load Control
Conventional Day VFR
Air Combat

These tasks require a visual system with a uniquely wide range of performance. The most stringent requirements flow primarily from the NOE mission with its out-the-window visual scene incorporating near and far field objects that are viewable over a significant percentage of full field. These objects represent scenes that are rich in detail. This places a heavy requirement on image generation capability particularly when realism is needed for pilot acceptance.[10] For the purposes of ACAVS preliminary design and development, it has been found that visual display and CGI technologies have in common only a small number of well defined interactions. Primary emphasis in this paper is placed on the display concept as the visual system design driver.

For clarity, the specific requirements associated with visual display systems and those associated with image generation will be discussed separately.

Display Systems Requirements

Specific display performance requirements that were used in the ACAVS display system preliminary design are shown in Table 1.

Table 1. ACAVS Display Performance Requirements

Parameter	Minimum	Goal
Field of View	120°H x 60°V*	240°H x 180°V
Image Resolution	6 arc Min.**	3 arc Min.**
Brightness	.03 – 30 fL	.03 – 50 fL
Color	2 Color	Full Color
Contrast Ratio	.03 – 30	--
Slew Rate	60°/Sec	100°/Sec

*Instantaneous FOV, rotatable as a goal
**Measured in optical line pairs as seen at the display

Visual parameters most critical in ACAVS display system design are Field of View (FOV) and image resolution. A typical view polar of a large side-by-side rotorcraft that illustrates the demanding FOV requirements is shown in Figure 4. Other parameters of importance in the overall display system design are image brightness, color, contrast ratio, slew rate and distortion. A full discussion of the origin of these performance parameters is not within the scope of this paper.

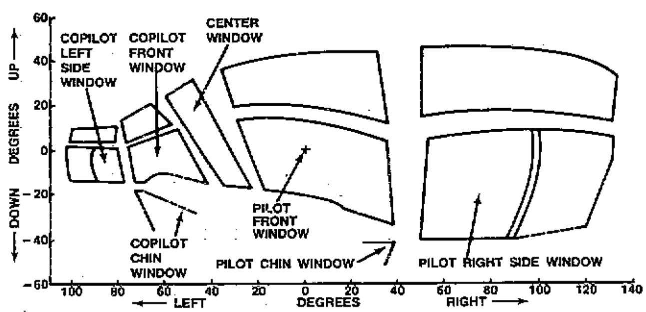

Figure 4. CH-46 Cockpit FOV from Pilot's Design Eyepoint (11)

The FOV requirements include a 60° downlook potential forward and to the side. A sketch of the percentage of full field view is shown in Figure 5 for both the minimum requirement and the desired goal.

Resolution requirements are driven by the need to provide precise control of linear velocity that must occur near the terrain and to perform target tracking tasks that may include acquisition of targets at realistic distances. For reference, it has been shown that detection of a tank at 2000 meters requires a resolution of about three arc minutes per line pair[12]. Peripheral vision requires somewhat less resolution since the relative acuity of the eye drops to about 10% at 40° from the center of the fovea.

Visual Image Generation

Visual image generation is an important and complex part of visual system concept design. Even though the major thrust in this paper is directed toward display concepts, the discussion that follows offers an abbreviated overview of some major image generation design considerations.

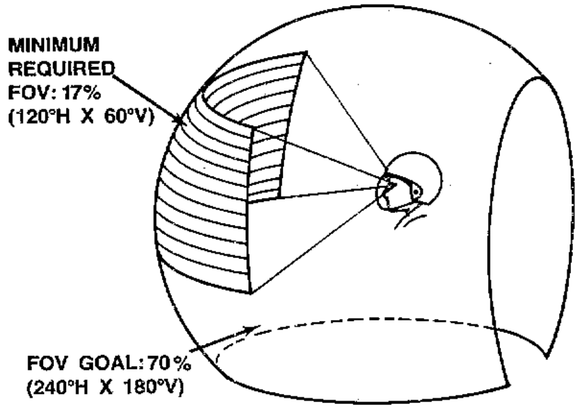

Figure 5. ACAVS Percentage of Full Field Vision

Visual Image Generation

There are many factors that influence image generation design. These include:

Field of view (FOV)	Image resolution
Scene detail	Level of detail control
Number of displayable edges	Moving models
Curved surface shading	Weapon effects
Color	Texturing
Frame rate	Atmospheric effects
Transport delay	Gaming area

Three of these factors have major impact on the design: Field of view, image resolution and scene detail. As in display system design, the product of field of view and image resolution is a basic performance measurement and relates directly to the number of pixels that must be computed in computer generated image systems (CGI). Scene detail is difficult to specify in such a manner that only those requirements are placed upon the CGI design that are directly related to the ACAVS mission task. This is an important consideration since it is generally accepted that any attempt to produce individual detail equivalent to the level perceivable by the human eye would be futile with present technology. However, texturing methods and memory intensive algorithms being developed show much promise.

TECHNOLOGY ASSESSMENT

A technical assessment of systems that will be viable for ACAVS in the 1982-84 time period indicates advancement of several visual system components. An assessment of six of these that show particular promise is given here:

1) Television projectors are nearing production that use liquid crystal displays with significantly lower scene lag by a factor of at least two compared with those previously available.

2) Scanning laser systems offer high resolution images over a larger field-of-view per projector than any other display system surveyed.

3) In-line virtual image windows are being made lighter weight and more light efficient by substitution of holographic elements for the heavy optical lenses.

4) Studies are available that show potential of expanding the field-of-view of large exit pupil virtual imagery systems to 70°V x 100°H.

5) High resolution fiber optics are being used to supply images for helmet mounted virtual image displays or for real image projection on large spherical screens.

6) An optical extension lens display technique is also available that will lower distortion caused by off-center projection spherical screen systems.

Further description of several of these display system components is provided in the discussion of various system concepts.

Image Resolution Factor

A factor basic to the information presentation ability for wide angle displays generation is related to the ratio of field-of-view and image resolution. Because of the interdependence of these parameters their product may be used and form a figure of merit which can serve as a comparison between potential ACAVS presentation sources (e.g., television projectors and scanning lasers). These parameters can normally be traded against each other in any specific system design. A comparison of several existing projection system capabilities is shown in Figure 6. It is noted that the scanning laser has an Image Resolution Factor significantly above the rest. However, if a third factor related to delivered brightness is considered, the light valve systems rate more favorably relative to the laser systems. For the purpose of this paper, image resolution is defined conservatively such that an interlaced television raster display consisting of 1000 viewable lines subtending a total vertical angle of 36 degrees to the eye is said to have 6 arc minutes of resolution per line pair (assuming a Kell factor of .71).

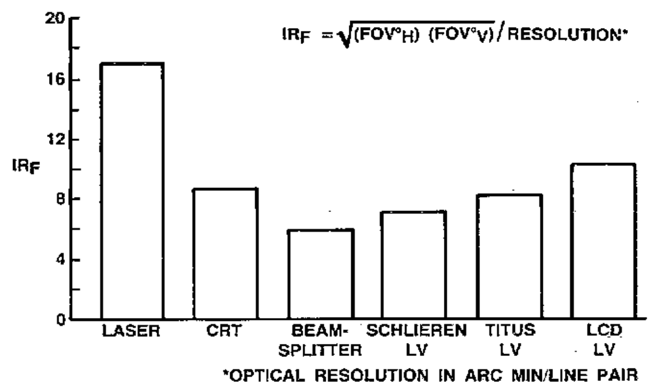

Figure 6. Projector Image Resolution Factor

ADVANCED DISPLAY SYSTEM CONCEPTS

Four feasible display system concepts can be postulated that incorporate one or more of the technology advancements assessed above. The order in which these concepts are discussed below is unrelated to their preference as potential RSIS simulator designs. The first three concepts discussed utilize a spherical screen the external dimension of which is limited to 20.5 ft in order to clear the walls of the VMS facility under all rotational and translational excursions. The performance characteristics given are for selected display projectors only. Any of the projector types evaluated in Figure 6 are potentially usable although system efficiency may limit use of those with lower light output. All slewable display scenes will project 60 degrees downward.

Light Valve and Extension Optics Concept

This relatively conventional configuration uses three light valve projectors combined with extension optics. The concept is depicted in Figure 7. The extended "periscope" design of the optics allows the placement of lenses near the center of a spherical screen to minimize distortion, channel matching and focus problems. A head tracker on the crew member's helmet controls the motion of the projector and optics in the pitch axis. Projector images are edge matched by masking inside the extension optics. Advantages of this concept are low design risk and high scene brightness. Disadvantages are lateral FOV limitations and resolution marginality.

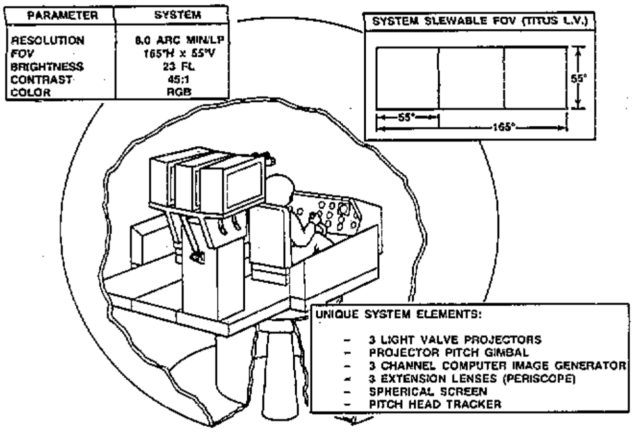

Figure 7. Light Valve and Extension Optic Visual System Concept

Light Valve and Fiber Optics Concept

In this concept flexible coherent fiber optic bundles transmit images to an optical head from three light valve projectors fixed to the crew station platform. The fiber optic bundles are frequency multiplexed to minimize the effect of individual fiber breakage. The optical head is gimbaled as shown in Figure 8. The gimbal is slaved to the motion of the crew members helmet in pitch and yaw and rotates about the exit pupil of the optics. The image is a composite designed with high resolution in the central area of the display by insetting one of the channels of 6.5 arc min/Lp resolution in a pair of lower resolution fields. Advantages of this approach include reduced gimbal drive power requirements and wider total field of view than the preceding concept.

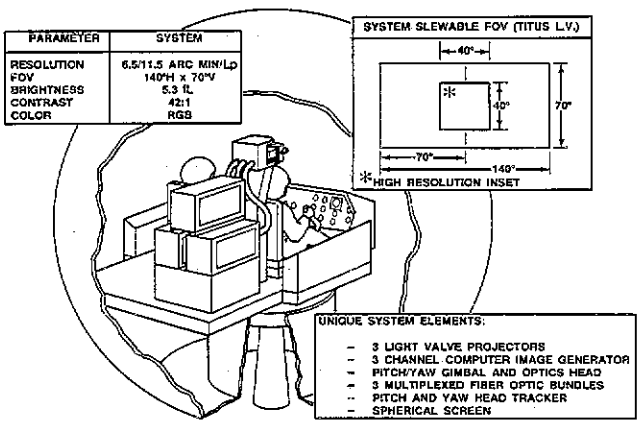

Figure 8. Light Valve and Fiber Optics Visual System Concept

A second approach (not shown) using the same light valve projectors and fiber optics eliminates the gimbal and adds a fourth channel to widen the instantaneous field of view. With this arrangement a 223-degree horizontal field of view with composite resolution fields is feasible at a brightness reduction to about 2.3 fL. This approach increases the reliability and instantaneous field of view but decreases the resolution on the sides to a marginal 13 arc minutes. There is also an undesirable 47-degree long horizontal "window" joint at the center of the display scene.

Scanning Laser Concept

The use of a scanning laser allows the projection of a bright collimated beam of light on a spherical screen with a vertical raster scan. As in the previous concepts, the scanner projector is positioned above the crew member's heads as shown in Figure 9. Because of the large depth of field the projector is not constrained to the screen center. The display is slewable in pitch and is slaved to helmet position in pitch.

Advantages of the laser concept are good resolution and wide instantaneous field of view. The large continuous scan requires special interface considerations with computer image generation hardware.

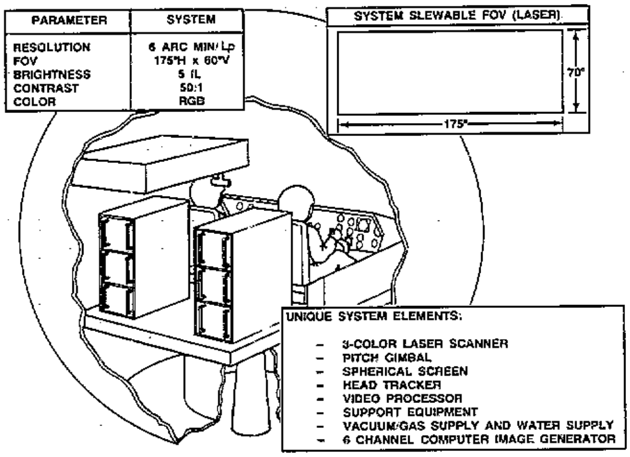

Figure 9. Scanning Laser Visual System Concept

Helmet Mounted Display Concept

In this concept a small virtual imaging system is mounted on a crew members helmet. Three light valve projectors relay the visual images to this Helmet Mounted Display (HMD) via flexible coherent fiber optic bundles. The three images are processed optically into two scenes, one for each eye, at the output of the projectors. The sketch in Figure 10 depicts a concept using two such systems.

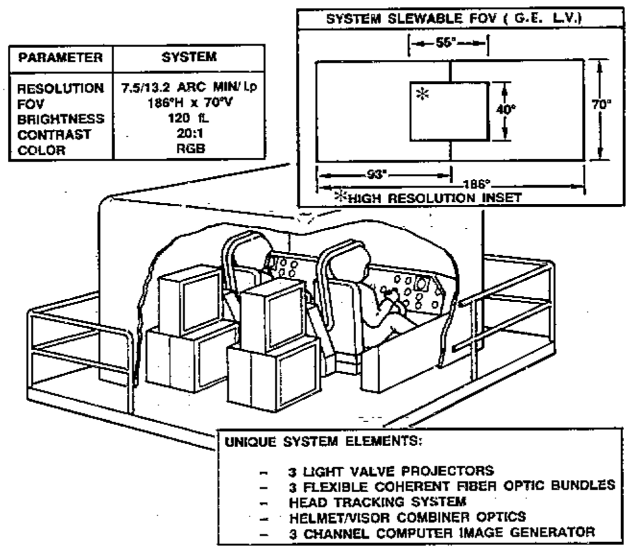

Figure 10. Helmet-Mounted Display Visual System Concept

The HMD has optical combiner lenses which permit "viewing" of the internal cab and instruments in the areas of view where the CGI image is blanked. Prior cockpit mapping provides cab interior polar plot information to blank the image. An artist's concept of this HMD blanking is shown in Figure 11. A head tracking system provides pilot head position information to the CGI visual system.

The advantages of the HMD approach are numerous. The concept offers effectively unlimited total field of view with a minimum of distortion. Illumination efficiency is adequate to allow a wide range of projector possibilities. Elimination of external screen or other optical elements allows a large space and weight saving. Disadvantages include some head encumberance and some incompatibility with actual aircraft helmet mounted hardware. However of all the concepts studied, the HMD uses the newest and least proven techniques and thus involves the highest risk.

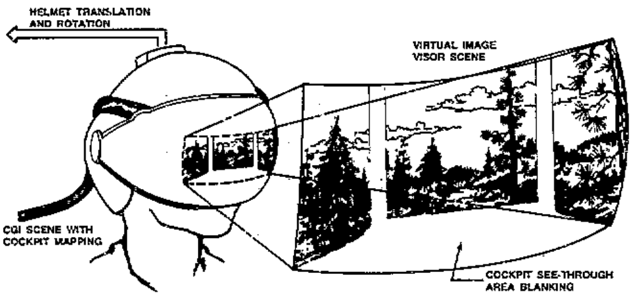

Figure 11. Helmet-Mounted Visor Display Blanking

VISUAL SYSTEM CONCEPTS EVALUATION

Although no single system concept (display concept and image generator) will completely meet all the requirements set forth by the RSIS program, any one of the approaches will provide a substantial portion. There is no imminent technology break-through that will exceed the ACAVS system requirements. Rapid progress is however, being made in the areas of helmet mounted displays, scanned laser systems and computer generated imagery. Some areas such as HMD will need to be addressed in further detail before a design decision is made to implement them in a system design.

Although proposed as a research and development device, ACAVS advanced visual system concepts employ many features that would seem to be valuable for many future flight trainers and especially, of course, rotorcraft flight trainers. Their wide fields of view coupled with high resolution allow a wide latitude for designers seeking to fulfill difficult training requirements associated with visual target acquisition and tracking, weapons delivery and landing as well as NOE flying techniques.

EXPECTED BENEFITS

The Army/NASA, 1975 study[4], concluded that the utilization of a helicopter R&D simulator fell into two categories:

a. Support of basic technology: This work consists of generalized or generic studies of stability and control, handling qualities, controls and displays, and other aspects of the man-machine interface.

b. Support of the development of new aviation systems or improvements to fielded systems: These efforts start early in an aircraft acquisition cycle by assisting the User and the Developer in performing design studies and system integration evaluations and trade-offs.

During recent years a coordinated program has been undertaken at Ames Research Center to provide a data base for helicopter handling qualities and control system design criteria. As indicated in Figure 12, advancements in rotor systems and their associated flight controls offer the most direct method of improving flying qualities and reducing pilot workload in the NOE regimes (Figure 1) where Army helicopters operate. Chen and Talbot[13], investigated four major rotor system design parameters to assess the handling qualities for 44 configurations of main-rotor systems which cover teetering, articulated and hingeless families of rotor systems with a wide range of blade inertia. They concluded that within each family of rotor systems, satisfactory handling qualities were obtained by appropriately adjusting the rotor parameters. No rotor system was

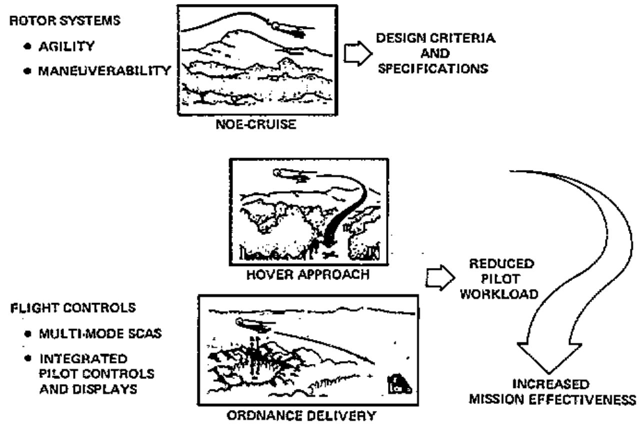

Figure 12. Helicopter Handling Qualities Research

uniformly superior in NOE handling qualities. It follows that additional experiments will be required to optimize the handling qualities for specific missions conducted in the NOE environment.

Aiken and Merrill[14] investigated control system variations for an attack helicopter mission. This was part of a major area of research aimed at reducing pilot workload of highly maneuverable helicopters that are intended to function as stable platforms for target designation or weapon delivery at night or under adverse weather conditions. Two candidate techniques are under investigation: (1) modifications to the control system, and consequently the handling qualities, as a result of different flight modes; e.g. – cruise, approach to a hover, hover, bob-up, pop-up, etc; and (2) variations in the method by which critical information is displayed to the pilot. Both of these techniques have great potential for reducing pilot workload and additional experiments are planned.

The uses of R&D simulators in the development of new aviation systems or improvements to fielded systems follow the life cycle of system development. During the program initiation phase, the simulator can be used to evaluate new aviation design concepts that have been developed by the U.S. Army Training and Doctrine Command (TRADOC), to meet a specific threat. This evaluation can help answer the questions and support the rationale leading to a Mission Element Needs Statement (MENS). After the MENS is approved, the R&D simulator can be used in the demonstration and validation phase for evaluating the flying qualities of competing designs as well as the ease of future systems integration efforts.

Finally, the simulator can be used for engineering development and product improvement. As the design evolves, either on paper or as a result of initial flight testing, changes to correct shortcomings in either flying qualities or total performance can be evaluated for their effectiveness as well as their undesirable side-effects. Project managers can also use the simulator to evaluate product improvement proposals prior to actual hardware fabrication and expensive flight qualification.

Flight simulation is an important tool in helicopter research and development, both for technology base development and for aircraft development programs. The RSIS will be a unique capability for use by both government and industry in an effort to maintain our current lead in helicopter development and production in the free world.

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Addendum: Funding of certain research and development projects involving liquid crystal display and holographic lense elements technologies has been withdrawn. This will, in all probability, jeopardize the availability of these technologies for the RSIS Program.

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