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# THE ROLE OF THE RESEARCH SIMULATOR IN THE SYSTEMS DEVELOPMENT OF ROTORCRAFT

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## SUMMARY

Over the last 20 years, flight simulators have become widely accepted as training tools. Moreover, research simulators have been used extensively by the fixed-wing industry in the design, testing, and certification of new aircraft. The rotorcraft industry, however, has been slow to use man-in-the-loop simulation to solve its design problems, primarily because of the difficulty of modeling complex rotorcraft for real-time simulation and because of the need for a wide-angle visual system for low-level flight. A joint U.S. Army and NASA program has been initiated to provide this simulation capability for exploitation by both government and industry. This paper, a status report of that program, discusses the potential application of the research simulator to future rotorcraft systems design, development, product improvement evaluations, and safety analysis.

## 1. INTRODUCTION

Although the U.S. Army accepted delivery of its first helicopter 40 years ago, it was not until after the Korean War that the necessary doctrine and experience were available with which the development of a military helicopter could be begun in earnest. The greatest impulses to and progress in helicopter development resulted from the requirements and experiences in the Korean, Viet Nam, and Middle East wars.

In the three decades since the end of World War II, the U.S. Army has considerably expanded its use of the helicopter. Originally, the helicopter was thought of as being a reconnaissance, evacuation, and general-purpose aircraft that was capable of performing missions similar to those that had been performed by the light, fixed-wing aircraft. As the potential of this vehicle began to be appreciated, its use added another dimension to the battlefield by enhancing the Army's ability to conduct the land combat functions of mobility, intelligence, firepower, combat service support, and command, control, and communication. Helicopters are now recognized by the U.S. Army as important replacements for traditional ground vehicles in the performance of certain missions that are beyond the capability of fixed-wing aircraft. As the helicopter has acquired these new missions, it has also acquired new tactics, new performance requirements, and a tremendous increase in the number of subsystems, most of which require some degree of management or control by the pilot. The typical Army aviator today is expected to manage the flight-control systems, the navigation and guidance equipment, the target acquisition and designation systems, the weapon systems, the electronic countermeasures systems, the identification systems, and the communication systems — all while he is flying close to the ground, maneuvering around and between obstacles, possibly at night and in adverse weather.

As an example of the current situation, Table 1 shows some of the systems in the new Advanced Attack Helicopter, the AH-64, over which the aircrew must maintain some degree of management or control. In addition, there are a Hellfire missile subsystem, a 30-mm chain-gun subsystem, an aerial rocket subsystem, an external stores subsystem, and the fire-control subsystem. As another example, consider the comparison of the cockpit displays shown in Fig. 1. The OH-13 display provided only essential flight information; that of the UH-60 provides information tailored to that helicopter's mission.

Considerations of cost have played a role in this tendency toward more mission complexity for each aircraft. If the current trend of exponentially increasing costs continues over the next 40 years, it is estimated that the entire U.S. Air Force budget would be required to fund a single aircraft system. Significant progress has been made in designing systems for reduced production and support cost, in utilizing new technologies to reduce cost, and in evolving the systems acquisition and logistics management processes which exert a major influence on life-cycle cost. However, there has been little progress in the most costly area, namely, that of setting the requirements, and, today, when a U.S. military service finally obtains approval to build a new aircraft, it frequently tries to make that single system do everything. As a consequence, it is reasonable to expect that the next generation of military helicopters will be even more complex and expensive than current helicopters, with even more subsystems for the pilot to manage.

Training alone may no longer enable the pilot to cope with the situation. It is possible that regardless of the extent of training, we are approaching the limit of the human pilot's capability. Of course, the helicopter could be made easy to fly or even to fly itself in these new missions, but such benefits are costly. Automation can significantly increase cost and complexity, and adversely affect reliability and maintainability. To be cost effective, the military helicopter must make full use of its pilot and his capabilities. However, he must not be overloaded to the extent that his mission performance is degraded or his margins for error are decreased until there is an increased susceptibility to accidents. Ground-based flight simulation is the only practical way to investigate the trade-offs systematically before hardware is developed.

Over the last 20 years or so, ground-based flight simulation has become a recognized and widely accepted training tool. In the fixed-wing aircraft industry, the cost effectiveness of ground-based flight simulation in research and development has already been demonstrated (Ref. 1). It has become a primary tool in the fields of dynamics, control-system development, and human factors. 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 are just a few examples of the many uses of the modern flight simulator. Recent emphasis on the control of development costs and on the conservation of fuel have enhanced the increasingly important research and development role played by flight simulators.

Although flight simulators have been widely used by the fixed-wing industry for many years, they have been used to a far lesser extent by the rotary-wing industry. In 1971, the U.S. Army initiated an extensive program in the use of simulators for training helicopter aircrews when it introduced the UH-1H Synthetic Flight Training System. Since then, training simulators have been developed for the CH-47 Chinook, AH-1 Cobra, and the UH-60A Blackhawk. A contract for the development of the AH-64 weapons system trainer is expected to be awarded this year. Similarly, the U.S. Navy introduced a weapons system trainer for the SH-2F Seasprite in 1976 and has systems under development for the CH-46E Sea Knight and SH-3H Sea King. However, in contrast with the fixed-wing aircraft industry, there has been only limited use of man-in-the-loop simulation during the research and development phases of rotary-wing aircraft.

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. In the course of this review, the deficiencies in current simulation capability relative to rotary-wing aircraft requirements were identified. As a result of that review (Ref. 2), 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. The simulation capability is being developed jointly by the U.S. Army and NASA at Ames Research Center. This paper is a status report of that program.

## 2. USES OF A ROTORCRAFT SIMULATOR IN RESEARCH AND DEVELOPMENT

The introduction of sophisticated control techniques means that the matrix of possible aircraft behavior is so great that only pilot participation can separate acceptable and unacceptable handling qualities. As a result, simulation provides a tool for the research worker to use when investigating new aircraft characteristics and when optimizing them in the operational task. It allows the designer and the development engineer to "fly" a complex vehicle in a variety of configurations, throughout its operational envelope, and beyond, and with all the failure modes.

But simulation is now even more than that. There have been spectacular advances in simulation techniques during the last decade, and simulation now penetrates all aspects of aerospace activity. It permits the study of various piloting tasks and operational tactics, the development of guidance systems, displays, weapon systems, cockpit layout, and, in fact, all aspects of the operation of aircraft that affect the pilot, both in his performance as a controller and as a manager. The widest use of all, of course, is in the training of aircrews. In the civil field, simulation has made possible zero flight time when crews are advanced to new aircraft; in the military field it is moving toward complete mission training on the ground (not yet successfully achieved).

Flight simulators can be used to train better pilots or to develop better aircraft. The latter application is addressed in this paper. The review performed by the U.S. Army and NASA (Ref. 2) pointed up the need for studying the interrelated elements of the rotary-wing aircraft system: the human pilot, the flight-control system, the displays and vision aids, the navigation and guidance equipment, the weapons systems, and the ever-changing environment. In the final analysis, it is the optimum cooperation between the two dynamic systems – the pilot and the aircraft – that is decisive for the success of a flight mission. Therefore, it is important to study the behavior of both the pilot and the aircraft as well as their mutual influence, and to define the criteria of good handling qualities and of the handling limits of the system.

There are three types of simulation: nonreal-time, real-time (man-in-the-loop), and in-flight. Today, in the fixed-wing industry, these three simulation phases are used in an integrated approach during design, development, and evaluation of new aircraft weapon systems. The more complex and expensive techniques are used to validate and improve the credibility of the simpler, more economical, and more flexible approaches. This approach provides early identification of problem areas and an associated risk reduction. Manned, ground-based simulation is an important link in the design, development, evaluation, and training process for advanced aircraft weapon systems.

The 1975 Army/NASA study concluded that the needs for a helicopter R&D simulator fell into the following two categories:

1. In support of basic technology. This work consists of generic studies of stability and control, handling qualities, controls and displays, and other aspects of the man-machine interface.

2. In 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, system integration evaluations, and trade-offs.

The first of these uses permits us to address the fact that current helicopter flying qualities specifications are based on an obsolete design standard. For our newest helicopters, we have had to devise poorly substantiated criteria for new missions and tasks. Therefore, in our current R&D program we are pursuing the development of a technological data base in rotorcraft handling qualities that should enable us, for the first time, to generate knowledgeably the criteria and the specifications on flying qualities for rotary-wing aircraft designed to perform military missions (Fig. 2). Ultimately, the intent is to provide the designer with the matrix of information he needs to relate effectiveness to life-cycle costs.

The development of a handling-qualities specification for use by helicopter manufacturers in the design phases would benefit both the industry and the government. Experience has shown that the use of the current handling-qualities specification (MIL-H-8501A) has failed to provide more than basic guidance to industry, and attempts to meet the requirements of that specification have, in many instances, resulted in undesirable flying qualities (Ref. 3). Individual specifications were developed for the Utility Tactical Transport Aircraft System (UTTAS) and the Advanced Attack Helicopter (AAH) in an effort to eliminate this deficiency, but both helicopters, although judged to have superior flying qualities, also failed to meet certain requirements of their specifications (Ref. 4). From an aeromechanics point of view, our most modern U.S. Army aircraft, the UTTAS and the AAH, are based on technology that is 10 to 20 years old. These aircraft, like their predecessors, will impose workloads on their aircrews during typical Army missions that will constrain the pilot from exploiting to the maximum the full capabilities of his aircraft, especially at night or under adverse weather conditions.

To provide a basis for the development of a new handling-qualities specification, it is necessary to improve our handling-qualities data base in three general areas: (1) static and dynamic stability; (2) control power and damping; and (3) controller characteristics. Items (1) and (2) have the highest priority because they can influence basic design parameters of the helicopter. Controller characteristics are less critical early in design but have a major effect on pilot workload. For this reason, data need to be gathered on the characteristics of side-stick controllers for the next generation of helicopters; for example, the number of axes to be controlled (two, three, or even four), the helicopter response for each controller degree of freedom, and the relative advantages and disadvantages of force command or displacement controllers.

Rotor systems and their associated controls offer the most direct method of improving flying qualities and reducing pilot workload in the missions and tasks typically assigned to Army helicopters. Chen and Talbot (Ref. 5) investigated four major rotor system design parameters to assess the handling qualities for 44 configurations of main-rotor systems that 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 could be obtained with the appropriate combination of rotor parameters. However, no single rotor system was uniformly superior in all aspects of handling qualities during typical operations. Additional experiments such as these are required to optimize the handling qualities for specific missions.

A topic not treated well in any existing flying-qualities specification is the interaction of flight control and aircraft response characteristics with displays and vision aids. Aiken and Merrill (Ref. 6) investigated control-system variations for an attack helicopter mission. This was part of a major area of research at Ames Research Center that is 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 to the handling qualities, as a function of the flight mode (e.g., cruise, approach to a hover, hover, and bob-up); and (2) variations in the method by which critical information is displayed to the pilot. Both of these techniques have been shown in ground-based simulations to offer potential for reducing pilot workload. Studies of the man-machine interfaces need to be made in a flight simulator to develop a data base on the interrelations among cockpit controls, displays, mission performance, and workload. Such a technology base will allow sensible choices to be made during conceptual system synthesis and allow handling-quality specifications to be improved.

The second use of R&D flight simulators, during the development of new aviation systems or improvements to fielded systems, follows the entire life cycle of system development. During the program initiation phase, the simulator can be used to evaluate new aviation concepts or tactics that have been developed by the U.S. Army Training and Doctrine Command (TRADOC) to meet a specific threat (Fig. 3). The ground-based flight simulator has considerable potential not only in developing tactics for a given aircraft and its weapon system, but in assessing and exploiting the various factors that influence the combat capability of a generic aircraft system. Combat simulation can be used to indicate trade-offs and exchange rates, considering the costs of such factors and other design features as well as the resulting effectiveness in a particular mission. The potential value of combat simulation is, therefore, enormous — it provides an efficient way to address design issues of new aircraft at the time that requirements are being established. Most of the life-cycle costs of an aircraft are determined once the requirements for that aircraft have been specified. Consequently, the important trade-off decisions must be made very early, when the tactical utilization and the conceptual designs are still in discussion. The R&D simulator also provides an ideal environment for evaluating the threat from both ground weapons and enemy helicopters (Fig. 4). The probability of air-to-air combat between helicopters on the future battlefield is extremely high. Success in these engagements may depend on exploitation of weakness in the threat helicopter's handling qualities or in the optimization of our own flight maneuvers. It may be in this approach to establishing requirements that ground-based simulators will play their most effective role in minimizing the life-cycle cost of our future aircraft. Such evaluations 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 (Fig. 5) for evaluating the flying qualities of competing designs as well as for easing future systems integration efforts.

Recently, from developments in the fixed-wing industry, there has come a realization that the benefits of active control technology can only be realized if they are considered during the initial selection of the aircraft configuration for the designated mission. By introducing control concepts as an element in the trade-offs during initial design studies, certain benefits in performance and efficiency may be realized through reliance on the capabilities of a flight-critical automatic control system. However, handling-qualities criteria for helicopters in military missions do not exist; consequently, evaluations such as these that depend on subjective ratings can only be obtained during initial design studies in a man-in-the-loop, ground-based flight simulator.

Consequently, manned simulation plays an important role in establishing hardware configuration during the development phase (Fig. 6). During the evaluation phase of a baseline design, test pilots and operational pilots are provided the opportunity, through manned simulation, to evaluate the baseline and mission scenarios with full operational freedom. This is the last point in time when changes to the baseline

design can be made without extremely costly hardware retrofit. Also, actual prototype flight hardware can be incorporated into the flight simulator. Although standard bench integration tests will verify electrical and, in some cases, software compatibility, only a dynamic simulation can completely exercise the equipment. Even more important, all aspects of the software can be tested in a mission environment well before the aircraft flies. In addition, training of test pilots for the formal flight-test program enables procedures to be developed before flight.

The use of flight simulation is expanding rapidly, particularly as mission systems become more complex and more highly integrated. The aircrew workload involved in subsystem management, particularly in a combat environment, can of course be drastically altered by crew station design and system automation techniques. With the wide assortment of advanced display systems and control techniques available to the crew station designer, it is imperative that crew station design begin at least as early as the airframe design. It is in this area that manned, ground-based simulation can probably contribute the greatest amount of guidance.

The cost and mission effectiveness of improving an existing system (Fig. 7) versus developing a new system can also be assessed on the flight simulator. Modifications or improvements to an existing system can create new problems, especially if those changes are developed piecemeal and by different agencies. For example, the Preliminary Airworthiness Evaluation of the OH-58C, an improved version of the OH-58A, revealed that not only did all the deficiencies of the A-model remain but eight new shortcomings were identified (Ref. 7).

Finally, the R&D simulator can be used to investigate unusual accidents, the understanding of which defies normal investigative techniques. One such investigation has already been accomplished at Ames Research Center. In March 1976, a Bell Helicopter Textron Model 214 helicopter crashed during hardover-control-signal testing of its Automatic Flight Control System (AFCS). The subsequent accident investigation did not conclusively establish the cause of the accident but did indicate that it was not caused by a mechanical, electrical, or hydraulic failure. It was decided to continue the investigation using the six-degrees-of-freedom Flight Simulator for Advanced Aircraft (FSAA) at Ames Research Center. Although this simulator is quite limited in vertical motion and field of view, it was considered adequate for this task. The results proved that removing the hardover-control-signal at the same time the pilot was taking corrective action causes large spikes in blade flapping and was the probable cause of the accident. The procedure for hardover-control-signal testing was subsequently modified and similar accidents have not recurred.

In summary, flight simulation is an important tool in helicopter research and development, both for technology-base development and for aircraft development programs. There is no question that ground-based simulation has been and will continue to be an invaluable tool. The flight simulator is to the flight dynamicist what the wind tunnel is to the aerodynamicist. The emphasis on the control of development costs and operational training costs suggests that flight simulators will play an increasingly important role in future research and development of rotary-wing aircraft.

## 3. REQUIREMENTS OF A RESEARCH AND DEVELOPMENT ROTORCRAFT SIMULATOR

### 3.1 General Requirements

The modern battlefield has become a highly lethal place for both fixed- and rotary-wing aircraft. The formidable array of weapons that can be used against aircraft has forced pilots to abandon their normal operating altitudes in the vicinity of a battlefield. The only air space that can be considered relatively safe is below 100 ft and then only if a sufficient amount of ground cover is available. The helicopter is naturally a ground contact machine par excellence and its mission use in Army aviation is more characteristic of a flying jeep or tank than of an airplane. Helicopters fly low and slow and, especially during military missions, are close to the ground during most of their flying time. The term nap-of-the-Earth (NOE) (Fig. 8) has been coined by the helicopter community to describe operations in which helicopters 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 — trees, bushes, hills, and valleys. Although these terrain features offer protection from the enemy, they can be lethal to an unwary pilot. In addition, visibility factors associated with 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.

Current simulation capabilities cannot meet the requirements of rotary-wing aircraft when one considers all the aspects, including mission, task, 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 simulators. The most advanced ground-based simulators in the world are available to the U.S. Army's Aeromechanics Laboratory (through agreements with Ames Research Center), but even these are not adequate to meet the Army's need to simulate nap-of-the-Earth flight operations. The visual display is required to represent much more detail in the terrain and vegetation. Low flight speeds and high maneuverability allow rapid changes of flightpath to be achieved so that the field of view required for the helicopter pilot to see where he is going is wider than that of a fixed-wing aircraft.

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 flightpath. In a helicopter, especially at speeds approaching hover, pitch attitude becomes less effective in controlling flightpath angles and becomes a better control of speed, while another control, thrust, is required for rate of climb. In addition, heading is no longer controlled by bank angle but also requires an additional specific input through the yaw control. Thus, the pilot's control problem becomes much more complex; he must now work all four controls.

These characteristics of helicopters and VTOL aircraft, in conjunction with their missions, create a greater need for motion and visual cues in their simulator systems than is necessary in similar systems for fixed-wing aircraft. Also, the mathematical model required for a reasonable representation of a helicopter is more complex, for it must contain some elements of rotor dynamics. 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. Furthermore, although there are many helicopter training simulators, the requirements of the flight simulator in the research and development role and in the training role are different. In the former case, we are concerned with the development of the complete flying machine; in the latter, we are concerned with the development of the man. In the development of the machine, it is important for a valid assessment of the vehicle that the pilot adopt the same control strategy in the simulator as in the air. In the training role, it is not obvious that an identical control strategy by the pilot is necessary for the transfer of skills.

The characteristics of the simulator hardware components that have maximum cost and technological effect are: (1) motion system characteristics, such as the number of degrees of freedom, scaling of cues, smoothness, bandwidth of response matching, and ext of miscueing; (2) visual display characteristics, such as field of view, resolution, detail, and dynamic response; and (3) the accuracy of the mathematical model, that is, the mathematical representation of the simulated aircraft. The requirements that have the greatest effect on the characteristics of these three components will be discussed in turn.

## 3.2 Motion (Platform) Requirements

Motion and orientation perception integrates four sensory modalities: vestibular, visual, nonvestibular proprioceptive, and tactile. Although the sensors are largely physiological components, the biological control processor which integrates information from the various sensors is strongly influenced by psychological factors.

There exists no obvious and accepted measure of motion cue requirements. An attempt to promote systematic and complete physical descriptions of motion systems is to be found in the work of the AGARD FMP Working Group 07 (Ref. 8) but that group did not address the relation of the identified metrics to pilot cueing capabilities.

Just because certain motions and forces are present and perceived in flight does not necessarily mean that they are important in performing or learning certain flying tasks. On the other hand, motion cues in flight simulation can be important even when adequate alternative visual cues are available and even for the study of head-up display presentations. Motion is important because of the proved effect of a motion platform on the gain and phase of the pilot's control inputs. There are relatively few cases in which motion is not needed as a limited displacement onset cue.

It is generally agreed that motion simulation is required to obtain the full potential pilot performance. In a more specific sense, motion simulation is required: (1) when expected motions are above human sensory or indifference thresholds; (2) when expected motions are within the sensory frequency range, that is, above 0.2-0.5 rad/sec; (3) if full pilot performance (e.g., tracking) is desired; or (4) when a degree of face validity or realism is required to gain pilot acceptance of the total simulation.

An example of relating simulator motion system capabilities to the maneuver envelope of an aircraft is presented in a paper by Key et al. (Ref. 9), which includes a description of the development of the requirements for a motion system to be used in a helicopter flight simulator.

The criteria that were adopted for these requirements were based on the opinions of experienced researchers, which in turn were supported by limited test data. In essence, the criteria relate the maximum allowable distortion of angular velocity and apparent force in the simulator to that of the simulated aircraft. This distortion is considered at the discrete frequency of 1 rad/sec; rotational sensing is best at the 1-rad/sec frequency. Figure 9 describes the fidelity of the motion in terms of the phase distortion and amplitude of the angular velocity and specific forces observed in the simulator relative to those of the helicopter cockpit that is being simulated. After hypothesizing the suitable motion washout algorithms, it is possible, by flying extreme maneuvers, to determine the required performance (i.e., excursion, velocity, and acceleration) of the motion platform.

Flight maneuvers resulting from fixed-base simulations of NOE flight operations were analyzed in this way to define the platform excursion requirements. These time histories were played (off-line) through a drive logic representing that of an advanced six-degrees-of-freedom simulator, with the fidelity boundaries and selected operating points for each axis, as shown in Fig. 9. The results of the analysis, in terms of the maximum excursion, velocity, and acceleration of each axis, are presented in Table 2. The requirement is that all axes produce these quantities simultaneously; this requirement is amplified by the data of Table 3, where the position of each axis at the instant that one axis reached a maximum is presented. The data are from a typical maneuver case, using the optimized drive logic described above. The significance of the data is that when one axis is at a maximum, some of the others are at large values also. A nonlinear drive logic is needed to vary the gains and washout frequencies with amplitude of motion in order to obtain as much fidelity as possible for lower amplitude tasks.

Specification of threshold performance insures a smoothly operating device devoid of the bumps and jerks characteristic of platform motion systems. Angular motion thresholds have been shown to be frequency dependent, and all values are a function of pilot task loading. The values adopted (Table 4) are approximations to the available data.

## 3.3 Visual System Requirements

The out-of-the-window visual scene is not only important for orientation; visually induced motion cues can also provide an extremely effective way of producing the illusion of sustained linear or angular velocity in a flight simulator. However, setting requirements for an out-of-the-window visual system for a simulator and the trade-off of these requirements with available visual system hardware is a vexing problem. The initial approach is usually to determine the gross performance of the human visual system and then to set the requirements of the ideal visual system to match the performance of the human eye. This approach results in impractical requirements because of the fantastic performance capabilities of the human eye. It is apparent that duplication of motion cues in a ground-based simulator is neither technologically nor

economically feasible; it is less obvious but equally true that duplication of visual cues, at least at this time, is also technologically unfeasible. The requirement for a complete reproduction of the aircrew's available visual cues will be compromised just as surely as will be a requirement that the pilot's available motion cues be totally duplicated.

Trade-off decisions have to be made to provide a solution that is feasible both technically and economically. Consequently, it is important to identify, for any particular application, those features of the visual scene that are of overriding importance and to select the appropriate technique of scene generation. Unfortunately, the manner in which pilots make use of their visual capabilities is not clear. Moreover, the effect on their behavior of the removal of information that they normally utilize (thus forcing them to substitute alternatives from the abundant redundancy often available) is even more obscure. There are no clear guidelines on how to make the trade-offs from aircraft mission requirements into human performance requirements and finally into simulator engineering specifications. However, the increasingly successful use of visual simulation equipment for training and for vehicle research and development has stimulated the development of better equipment and provided data and insights into system requirements.

One fact that is perfectly clear is that no one visual simulation concept currently available has all the desirable features for a given task; any one system is good in some respects but deficient in others. Also, the visual display that is adequate for a training facility may be inappropriate for a research and development flight simulator.

The report of the AGARD FMP Working Group 10 (Ref. 10) discusses the metrics of flight simulator visual systems. The factors upon which a comparison of visual simulation systems can be based and which are the drivers of hardware cost and complexity comprise various spatial, energy, and temporal properties.

The spatial properties are

1. Field of view: in simple terms, the larger the better.

2. Scene content: ideally the system should provide the level of detail and textural quality that is seen by the helicopter pilot during terrain flight.

3. Range: that is, whether the optics are collimated or can depict objects on the ground at the correct focal distance.

The energy properties are

1. Luminance: should be sufficiently high to maintain the illusion of a day scene rather than a dusk scene.

2. Contrast: conveys information regarding spatial relationships among objects in the scene and between the pilot and the scene.

3. Resolution: that is, the ability to present small, recognizable details.

4. Color: its need in simulation is debatable, but it could be an important factor in tasks requiring detection and recognition.

The temporal property is dynamic performance — the presence of lag, dead space, friction, or nonlinearity in the driving of the visual display or visual anomalies due to dynamic interactions within the visual system are potential sources of piloting difficulties.

The two most commonly used visual simulation systems are based on computer-generated imagery (CGI) or camera/model-boards. Two other systems have limited application — film (photographic) and shadowgraph. The limited operating envelope and the inaccuracies introduced by the distortion of the image in the film systems render them unsuitable for general application. Shadowgraphs are likely to remain of value only for special applications, such as the current sky/ground projectors. Model-boards offer the richest scene content but have fundamental limitations on operating volume. The scale of the model-board is obviously a critical parameter from several viewpoints. It should be as small as possible to allow a reasonably large operating area yet large enough to prevent depth-of-focus problems. A scale of 500:1 is probably the smallest that will allow a sufficiently high quality picture for NOE operation. Scale is determined by minimum operational height, which in turn is controlled by the bulk of the optical probe and by the depth of field achievable. The optical probe used in a camera/model-board system for NOE flight must be able to operate very close to the ground and to vertical objects, go between trees spaced only two or three rotor diameters apart, and it must have a sufficient depth of focus to provide good imagery for all objects within the field of view.

Until recently most visual systems were based on the closed-circuit TV/model-board technique. This technique is now rapidly falling from favor; its deficiencies, in terms of field of view, resolution, gaming area, flexibility, and installation costs, are well known, but most importantly it appears to have approached the end of its development potential. Its primary advantage over most other systems is its capacity for high picture content and, provided a suitable scale can be tolerated, good textural detail.

In contradistinction to the TV/model-board system, present day CGI suffers primarily from lack of picture content and textural detail, particularly in daylight scenes. Field of view and resolution remain problems, but are a consequence of the display device and thus strictly not a failing of the CGI scene generator. There is an urgent need for improved display devices to take advantage of expected developments in CGI. The digital nature of these systems seems to make them likely candidates for the rapidly developing field of digital matrix array displays, such as light-emitting diodes, liquid crystals, and thin-film electroluminescent displays. Currently, these displays cannot match conventional television display devices in resolution. However, the resolution is being improved constantly, the power densities are low, and very high brightness seems attainable.

Near-term improvements in CGI technology will be in edge capacities, data-base generation techniques, storage techniques, texture, field of view, area of interest displays, and, probably, utilization of very large-scale integration technology. New techniques of image enhancement and texturing are being developed. Although a fully dynamic system is not working yet and probably will not be for another year, the static scenes are impressive. The remarkable attribute of the latest technology is its ability to produce fully textured surfaces. This texture can be applied to any face and undergoes the same perspective transformations as the face; as a result, it remains coherent with the face at all times, thus providing the correct texture gradient cues that are so important for low-altitude flight. The main effect of this approach to texturing is that it makes it possible to produce highly complex scenes with relatively few faces. It has been estimated that texturing enhances the face capacity by a factor of between 10 and 100. The cost of computer hardware for a given capability continues to reduce (although the demand for more keeps costs up) and the techniques of utilization continue to improve.

Following are some considerations of the visual simulation system factors listed above as they are affected by the special requirements of simulating NOE flight operations of helicopters.

### 3.3.1 Spatial properties

The field of view of the visual system is critical to the accomplishment of simulator flight research tasks, but the importance of mission-relation to the design cannot be overemphasized. The situation that dictates the widest field of view is that of maneuvering during air-to-air combat, and this requirement is even more seve.e for the helicopter in one-on-one combat than it is for the fixed-wing fighter. In conventional high-altitude air combat, the adversary's attitude and location relative to the attacker's body axes comprise the primary information required. With helicopter air combat, this is not true; the low-speed, low-altitude, and low-thrust/weight capability of these machines makes combat near the ground more attractive because of enhanced concealment. This means that a high-resolution, wide-field display of both the adversary and the ground is required.

For NOE point-to-point flying and hover operations, the necessary area of display is smaller than in air-to-air combat but still larger than in present day TV monitor-type displays. For example, studies of obstacle avoidance during NOE flight yields a requirement for a horizon-stabilized 120°-wide by 60°-high area centered at a point directly forward. This requirement results when one calculates the azimuth of a point 3 sec ahead during turning or sidestepping level flight. The value of 3 sec is considered the minimum preview time for obstacle avoidance. This means that a visual simulation display must be wide enough to show obstacles at least 3 sec ahead in the projected flightpath during turns or sidestepping. For example, a 2-g level turn (60° bank angle) requires that objects 3 sec ahead be visible at an azimuth of 60° for a speed of 50 knots. It also means that the display might have to be horizon-stabilized if the vertical field is small (40° or less) or else the 3-sec point (or objects) will lie out of the field when the aircraft is banked. This effect is illustrated in Fig. 10.

These considerations of NOE operations lead to ˥ field-of-view requirement of about 120° horizontally by 60° vertically that is horizon-stabilized in roll. Such a display can be centered directly forward. Flight at night introduces other considerations. Some preliminary tests at Ames Research Center suggest that although a helicopter can be hovered in daylight with a limited field of view, an increased field of view is required to provide the cues needed to control the aircraft in darkness. Hence, simulation of night out-of-the-window display puts considerable emphasis on providing peripheral cues.

The demand for wide-angle displays cannot be met with closed-circuit television systems because of optical problems in the TV camera. CGI can produce scenes for large viewing angles, but the displays presently on the market cannot produce a collimated continuous wide field of view. Although a wider field of view can be accommodated by simply adding more channels — that is, more windows in CRT-based systems — there are practical limits to this approach. Such approaches generate problems of image registration and window-to-window matching. Also, problems with size and weight develop rapidly for simulators with motion bases as more windows are added. The current demand for wide-field-of-view visual systems together with the rapidly expanding capabilities of the computer systems to generate the scene will require development of an advanced display device. Some possibilities are described in Sec. 4 of this paper.

Although CGI data bases can produce the field of view desired for NOE flight simulation, they have one major defect — lack of scene content. With CGI, the field of view and resolution are limited only by the price one is prepared to pay for the necessary computation capacity; however, the present practical problem is one of providing sufficient scene detail over a large area. Although current CGI picture generators are capable of producing sufficient polygons and lights to make a scene flyable, the scene that is presented to the pilot lacks one important feature that could add to scene content — texture. The polygons calculated by present-day CGIs, although shaded to blend the edges, are of uniform color. It is very difficult to locate such a polygon in space by judging its size and perspective area. The addition of texture to the polygon surface facilitates the task of judging the distance between the observer and the object, thus enhancing the three-dimensional effect of the picture and making the picture richer and more realistic. The problem is to develop techniques (e.g., adding texture) that will allow the density of detail to increase as features, such as hillsides, are approached, so that scene content is maintained at some sufficiently high level to provide the necessary cues to the pilot.

### 3.3.2 Energy properties

System resolution is almost always the first criterion mentioned in a specification for any visual system. However, it is not necessarily the system resolution that is important but rather what is presented to the pilot at his eye reference point. The criterion for acceptance in this application is the visual angle; that is, the angle subtended at the pilot's eye by the smallest element in the display. For night scenes, the ideal is to depict a point source of light at some photopic brightness level such that it would appear to be a true point source; this is relatively easily identified. However, for the daytime scene, selection of a single value for acceptable resolution in the display is arbitrary in the absence of flight-performance data. At the time the General Electric COMPU-SCENE was developed, 3 arcmin was the industrial capability of resolution of one line by one element.

The detection performance of the human eye is given in Fig. 11, in terms of threshold contrast, background luminance, and target size. The probable operating envelope of a research facility visual system is also shown for a minimum resolution of 3 arcmin. Most Earth features have contrasts between 0.03 and 1. The probable worst point is at high-brightness, low-contrast, and design resolution. It is seen that for the range of brightness shown, color is not always needed.

In many cases, the factors characterizing the visual system are not mutually exclusive, either in the ease with which they can be generated or in their contribution to simulation fidelity. For example, levels of contrast, luminance, and color can be interchanged while maintaining a given level of visual system complexity.

### 3.3.3 Temporal properties

What is an acceptable lag in a visual simulation system is the subject of some debate and confusion in definition. It clearly depends on the task and on the vehicle dynamics in that task; it will be a minimum in a tight loop-control task with a responsive aircraft. The control loops closed by the helicopter pilot generally have low damping and are close to instability at times. In these situations, any lag or time delay can have serious consequences, and systems like the TV/model-board, in which large pieces of machinery are moved around, must be suspect in terms of dynamic performance. The specification of dynamic performance for a CGI visual system is relatively straightforward, if there are no delays due to computation. Unfortunately, there are significant computation-induced delays; we are currently studying the allowable tolerances. There is evidence that only about 2% of the population could perceive lags in a visual system shorter than 125 msec, and lags shorter than 100 msec could not be perceived at all. Some discussion of this point is to be found in Refs. 8 and 10.

### 3.4 Computer Requirements

Another area that poses problems considerably more severe than those dealt with in conventional aircraft simulation is that of the mathematical model for real-time simulation of the helicopter. The aerodynamic forces and moments on a helicopter rotor depend on the radial distance from the hub and on the blade azimuth. The rotating blades are relatively flexible. In certain flight situations, parts of the blades enter nonlinear aerodynamic conditions, such as stall or high Mach number flow. Additional aerodynamic complexities occur because of interference between the airflow from rotor blades and that of the rest of the helicopter. The emphasis in helicopter operations on nap-of-the-Earth flying leads to particular consideration of ground effect. It has a large effect on aircraft trim and power, and when it is changing dynamically, as, for example, when flying over undulating terrain or crossing the deck edge of a ship, causes general unsteadiness. An added complication is the need to tie the ground-effect model intimately to the visual scene. The host computer must accommodate models of a wide variety of environmental factors. The most important of these are the basic atmospheric variations that affect aircraft performance and the wind turbulence and shears that add important realism to the simulated flight tasks.

There exist comprehensive mathematical models that attempt to take all of these features into account. However, such programs take very large computation capacity and run much slower than real time. Many simplifications have to be made for real-time simulation, but the extent to which this can be done depends on the application.

Table 5, developed by Chen of Ames Research Center, indicates a matrix of possibilities for mathematical models, based on including different representations of the aerodynamics and rotor dynamics. Linear aerodynamics implies simplifications, such as infinitely stiff rotor blades, small flapping and inflow angles, and simple strip theory, with no consideration of stall or compressibility. With such a model, much useful work of a generic nature can be performed (Refs. 5, 11). However, if it is desired to investigate boundaries of the flight envelope, then even in generic studies the effects of compressibility, stall, and other nonlinearities must be included. In simulations of specific helicopters, in which special quirks of a particular configuration need to be investigated, nonlinear effects may have to be included even well within the flight envelope.

A rotorcraft simulation capability to meet the needs of research and development must be able to represent the essential effects of nonlinear aerodynamics and at least the flap, lead-lag, and rotor speed degrees of freedom. To accommodate a mathematical model of this complexity without introducing a significant time lag, a very large general-purpose digital computer, such as the CDC 7600, CYBER 175, or some of the larger IBM 360 and 370 models, is required (Fig. 12).

### 4. RSIS PROJECT PLAN

Under joint agreement, Ames Research Center and the U.S. Army Research and Technology Laboratories, Aviation Research and Development Command (AVRADCOM), have agreed to acquire the Rotorcraft Systems Integration Simulator (RSIS) to be installed at Ames Research Center. The program is now in its final phase. The definition phase started with an Army/NASA study in 1975 which led to additional studies to address the issues raised by the special requirements of rotorcraft simulation. A feasibility study of a wide-angle visual simulation system, completed by Northrop in 1977, showed that a wide field-of-view display (120° horizontally by 60° vertically) was feasible. Analyses of fixed-base and motion-base simulations of NOE flight operations have defined the cab excursions required for high-fidelity simulation motion. It was determined that the Vertical Motion Simulator (VMS) at Ames Research Center could be modified and used as the motion base for the RSIS. Independent design studies to assess the possible modification to the VMS were performed by Franklin Research Laboratory and Northrop Corporation in 1978. Specifications were developed from those two studies, a competitive request for proposal was issued to industry, and the contract was awarded to Franklin Research Laboratory in 1979. The modification, known as the Rotorcraft Simulator Motion Generator (RSMG), will be delivered in late 1982.

The Vertical Motion Simulator (VMS) is a large man-carrying simulator now in operation at Ames Research Center (Fig. 13). 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. Eight dc servomotors drive the simulator 18 m vertically. Lateral motion capability of 12 m is provided by a carriage which is driven across the horizontal platform by four dc servomotors.

As a part of the RSIS program, the hydraulic motion system presently mounted on the structure that provides the vertical and lateral motion of the VMS will be replaced with the four-degrees-of-freedom Rotorcraft System Motion Generator (RSMG). The overall performance envelope of the combined device is projected to be as shown in Table 6. These peak motion system requirements are defined for a maximum payload that includes all hardware attached to the motion system with the following characteristics: weight = 3630 kg, moment of inertia = 850 kg-m$^2$, and a clearance envelope (cab and visual system) = 6.25-m-diameter sphere. The moment of inertia is referenced to a point 0.6 m below the sphere center.

The computation capability for the RSIS will be supplied by Ames Research Center's real-time simulation computation system, which is a network of computers and associated electronic equipment designed to perform the complex modeling and control functions of manned, real-time flight simulations. The facilities include a Control Data Corporation 7600 computer system and two Xerox Sigma series computers. These high-speed digital computers, which act as host computers, are used for solving the complex mathematical models representing the aircraft to be simulated. Several Digital Equipment Corporation PDP 11 series computers serve as front ends to the host computers.

A new interchangeable rotorcraft cab, a development station, and an advanced visual system are comprised in the Advanced Cab and Visual System (ACAVS) which will complete the RSIS project. The development station and interchangeable rotorcraft cab will enable Army/NASA researchers to release the VMS for experiments using other interchangeable cabs while the rotorcraft cab is reconfigured in the development station for the next experiment. Initially, the rotorcraft cab will be installed in its development station integrated with its advanced visual system and with the RSMG. This total system will be integrated with Ames Research Center's real-time simulation computation system into a fully functioning four-degrees-of-freedom simulator in the development station. It will be exercised as a four-degrees-of-freedom simulator in the development station for a period of about 1 year before being moved onto NASA's VMS. The concept of the RSIS project is depicted in Fig. 14. After completion of an initial simulation, the RSMG will remain as a permanent modification to the VMS and the cab will be moved back to its development station where it will be configured for its next experiment (Fig. 15).

The cab will be designed to provide for a variety of crew station arrangements, including two crew stations located side by side with the primary pilot on either the right or left, two crew stations located in tandem with the primary pilot in the front or rear, and a single pilot station. The primary and secondary instrument panels and consoles will be modular, permitting easy modification and replacement. A programmable sound-generator system will be capable of simulating the cockpit aural environment of the rotorcraft, including the rotor system or systems, the transmission, the engine, and ground reflection. The cab will include a programmable vibration generator system for the vertical axis that will vibrate the seats, controls, and instrument panels over a frequency range of 3 to 40 Hz at amplitudes of ±0.6 g or ±0.3 cm, whichever is less. The cab will be designed to accommodate and be compatible with special-purpose equipment, such as helmet-mounted displays and head or eye trackers.

The development station is the work area containing all associated equipment, systems, and utilities required to support the development and operation of the rotorcraft simulator cab and advanced visual system and to support the assembly, checkout, testing, and initial operation of the RSMG. As indicated previously, it will be used initially to support development, checkout, and integration of the major subsystems of the RSIS. Subsequently, the development station will be used to support off-line development of individual test setups (primarily cab configuration changes), thereby reducing fixed-base simulator experiments that utilize the cab and the advanced visual system.

The contract for the cab and the visual system will be awarded this year. The visual system will include the image-presentation system and the image-generation system. It will be capable of providing visual cues to a pilot for conventional terminal-area operations, landings at unprepared sites, sling load maneuvers, precision hover, nap-of-the-Earth flight, air-to-ground weapon delivery, air-to-air combat, autorotational landings, and ship landings. The system will be able to present all scenes under daylight, dusk, and night situations with variable weather conditions. The resolution of the presented scene will be no worse than 6 arcmin, with a goal of 3 arcmin for the background and 1 to 3 arcmin for targets. A minimum field of view of 120° horizontally by 60° vertically is required, with a goal of 240° horizontally by +120°, -60° vertically. A color capability of two basic colors is required, with full color as a goal. A scene illumination range of 103 cd/m$^2$ is required, with 171 cd/m$^2$ as a goal. These technical capabilities are summarized in Table 7.

We assume that a computer-image-generation system will be proposed by industry; however, any image-generation system that can meet or exceed our specifications will be considered. As a minimum, the special image-generation effects will include horizon glow for dusk and night scenes, one layer of fog or haze, and the capability to simulate an indistinct, hazy horizon. Special-effect goals include modification of imagery to simulate IR displays, rotor flicker effects, blowing dust or sand upon landing or low hover, target destruction or partial destruction, smoke, missile trail, patchy fog in low-lying areas, and cloud simulation. The deliverable data base will include a conventional airport, a helicopter stage field, an oil rig, and an NOE gaming area consisting of a 1.6 by 3.2 km terrain section. A variety of objects will be available for modifying the delivered data base including a variety of ground and air vehicles, trees, bushes, hedges, power poles, roads, streams, and buildings.

To provide us with a review of the rapidly advancing technology and to assist us in evaluating all of the trade-offs in the visual simulation area, a preliminary design study contract was awarded by the U.S. Army to Boeing Military Airplane Company, Wichita, Kansas. This study was completed in 1980 and provided the basis for the preparation of the specifications for the visual display for our new rotorcraft simulator. A summary of the results of this review is presented in Ref. 12.

The technical assessment of systems that will be feasible for our rotorcraft simulator in the 1982-84 period indicates that several advanced visual system components will be available. Four feasible display system concepts can be postulated that incorporate one or more of these technology advancements. In the first three concepts discussed below, a spherical screen is used. The performance characteristics given are for selected display projectors only.

1. Light-valve and extension optics concept: This relatively conventional configuration uses three light-valve projectors combined with extension optics. The concept is depicted in Fig. 16. 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 limitations on lateral field of view and marginal resolution.

2. 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 gimballed, as shown in Fig. 17. The gimbal is slaved to the motion of the crew member's 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 arcmin per line pair 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. 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° 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 arcmin. There is also an undesirable 47°-long horizontal "window" joint at the center of the display scene.

3. 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 heads of the crew members, as shown in Fig. 18. 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.

4. Helmet-mounted display concept: In this concept, a small virtual imaging system is mounted on a crew member's 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 Fig. 19 depicts a concept in which two such systems are used. 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 Fig. 20. A head tracking system provides pilot head position information to the CGI visual system. The advantages of the HMD approach are numerous. It offers effectively unlimited total field of view with a minimum of distortion; illumination efficiency is adequate to allow a wide range of projector possibilities; and elimination of external screen or other optical elements allows a large space and weight saving. Disadvantages include some head encumbrance and some incompatibility with actual aircraft helmet-mounted hardware. However, of all the concepts studied, the HMD uses the newest and least proved techniques and thus involves the highest risk.

5. CONCLUSION

We believe the time has come for expanding the role of ground-based flight simulation in the development of rotorcraft and other VTOL aircraft systems. Simulation technology has advanced to the point that most VTOL aircraft flying tasks can be simulated with a high degree of fidelity. The need for simulation has developed concomitantly with new mission assignments that have resulted in more complex systems and more difficult trade-off decisions. Ground-based simulation is the best way to systematically investigate all the trade-offs; it is the only way these trade-offs can be studied safely and on the ground, before hardware is developed.

We expect that the current U.S. Army/NASA joint program to develop the RSIS will result in a unique facility at Ames Research Center that will benefit the entire helicopter industry. Similar NASA facilities have been used extensively by European as well as U.S. fixed-wing industries; it is expected that the rotary-wing community will make a comparable use of this new facility. We are confident that the RSIS will be a major step forward in simulation capability and that it will prove as valuable in rotorcraft research and development as has its counterparts in the fixed-wing industry.

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TABLE 1. SYSTEMS IN THE U.S. ARMY ADVANCED ATTACK HELICOPTER, AH-64, MANAGED BY THE PILOT OR COPILOT/GUNNER

Intercommunications Subsystem
UHF Communications
VHF-FM Communications and Homing
VHF-AM Communications
Communication Security
Automatic Direction Finding
Doppler Navigation
Radar Altimeter
Heading Attitude Reference
Identification (IFF Security)
Crash Locator Beacon
Radar Warning
Target Acquisition and Designation Subsystem
Pilot's Night Vision Subsystem
Integrated Helmet and Display Sight Subsystem
Video Recording and Playback
Symbology Generator
Fire Control Computer

TABLE 2. MOTION (PLATFORM) REQUIREMENTS FOR CRITICAL TERRAIN FLIGHT MANEUVERS (from Ref. 9)

| Axis | Parameter | | |
|------|-----------|--|--|
| | Position, rad, m | Velocity, rad/sec, m/sec | Acceleration, rad/sec$^2$, m/sec$^2$ |
| Yaw | ±0.4 | ±0.6 | ±1.0 |
| Pitch | ±0.3 | ±0.5 | ±1.0 |
| Roll | ±0.3 | ±0.5 | ±1.0 |
| Surge | ±1.3 | ±1.3 | ±3 |
| Sway | ±3 | ±2.6 | ±3 |
| Heave | +7, -14 | +8, -11 | +14, -12 |

Notes: (1) The requirement is for simultaneous operation. (2) The rotational gimbal order is yaw, pitch, roll. (3) Translational axes are orthogonal; plus is forward, right, and down.

TABLE 3. EXAMPLES OF SIMULTANEOUS EXCURSIONS (from Ref. 9)

| Axis at maximum positon | Simultaneous axis position, % maximum | | | | | |
|------|------|------|------|------|------|------|
| | φ Roll | θ Pitch | ψ Yaw | X Surge | Y Sway | Z Heave |
| φ | 100 | 0 | 31 | 0 | 92 | 73 |
| θ | 60 | 100 | 6 | 83 | 46 | 14 |
| ψ | 67 | 22 | 100 | 28 | 54 | 41 |
| X | 33 | 33 | 19 | 100 | 0 | 59 |
| Y | 87 | 33 | 38 | 83 | 100 | 77 |
| Z | 47 | 33 | 0 | 56 | 69 | 100 |

TABLE 4. MOTION PLATFORM THRESHOLDS (from Ref. 9)

| Angular | | | Linear eleration |
|---------|--|--|------------------|
| Position | Velocity | Acceleration | |
| $\frac{0.2}{\omega}$ deg | 0 2 deg/sec | 0.2 ω deg/sec$^2$ | 0.01 g |

ω is in rad/sec.

TABLE 5.  ROTORCRAFT MATHEMATICAL MODELS FOR PILOT-IN-THE-LOOP SIMULATION

| Application | Model complexity[a] | | | | | | | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| | Linear aerodynamics, with simplifications | | | | | Nonlinear aerodynamics | | |
| | 1 | 2 | 3 | 4 | 5 | 1 | 3 | 5 |
| **General flying qualities — well within flight envelope** | | | | | | | | |
| Basic aircraft | | | | | | | | |
| Low-frequency maneuvers | X | | | | | | | |
| High-frequency maneuvers | | X | X | | | | | |
| SCAS research | | | | | | | | |
| Fuselage feedback | X | X | | | | | | |
| Fuselage/rotor feedback | | X | X | X | X | | | |
| **General flying qualities — full flight envelope** | | | | | | | | |
| Basic aircraft | | | | | | | | |
| Envelope exploration and maneuvering performance | | | | | | 1 | X | X |
| Boundary limiting and expanding SCAS | | | | | | | X | X |
| **Specific aircraft flying qualities** | | | | | | | | |
| | | | | | | X | X | X |

a1:  Fuselage and quasi-static rotor, 6 DOF.
 2:  Fuselage and rotor flap, 9 DOF.
 3:  Fuselage and rotor flap/rpm, 10 DOF.
 4:  Fuselage and rotor flap/lag, 12 DOF.
 5:  Fuselage and rotor flap/lag, pitch, rpm, 16 DOF.


TABLE 6.  MOTION ENVELOPE OF THE RSIS

| Mode | Displacement | Velocity | Acceleration |
| --- | --- | --- | --- |
| Vertical (Z) | $\cdot$30 ft ($\cdot$9 m) | $\cdot$20 ft/sec ($\pm$6.1 m/s) | $\pm$32.2 ft/sec$^2$ ($\pm$9.8 m/sec$^2$) |
| Lateral (Y) | $\pm$20 ft ($\cdot$6 m) | $\cdot$10 ft/sec ($\pm$3.0 m/s) | $\cdot$24 ft/sec$^2$ ($\pm$7.3 m/sec$^2$) |
| Longitudinal (X) | $\cdot$4 ft ($\cdot$1.2 m) | $\cdot$4 ft/sec ($\pm$1.2 m/s) | $\cdot$10 ft/sec$^2$ ($\pm$3.0 m/sec$^2$) |
| Roll | $\pm$18° ($\cdot$0.3 rad) | $\pm$40°/sec ($\cdot$0.7 rad/sec) | $\cdot$115°/sec$^2$ ($\pm$2 rad/sec$^2$) |
| Pitch | $\pm$18° ($\cdot$0.3 rad) | $\pm$40°/sec ($\cdot$0.7 rad/sec) | $\cdot$115°/sec$^2$ ($\pm$2 rad/sec$^2$) |
| Yaw | $\cdot$24° ($\cdot$0.4 rad) | $\pm$46°/sec ($\cdot$0.8 rad/sec) | $\cdot$115°/sec$^2$ ($\pm$2 rad/sec$^2$) |

Note:  The rotational gimbal order is yaw, pitch, roll; translational axes are orthogonal; plus is forward, right, and down.


TABLE 7.  RSIS VISUAL SYSTEM

| Parameter | Minimum | Goal |
| --- | --- | --- |
| Field of view, horizontal by vertical | 2.09 · 1.05 rad (120° × 60°) | 4.19 · 3.14 rad (240° · 180°) |
| Resolution | 1.75 mrad (6 arcmin) | 0.87 mrad (3 arcmin) |
| Luminance | 103 cd/m$^2$ (20 FL) | 171 cd/m$^2$ (50 FL) |
| Contrast ratio $[(B_1 - B_.)/B_.]$ | 25 | -- |
| Color | 2-color | Full-color |

(a) On 11, 1949.



(b) ca. 1978

Figure 1. Helicopter cockpit development.

ROTOR SYSTEMS

- AGILITY

- MANEUVERABILITY

DESIGN CRITERIA
AND
SPECIFICATIONS

NOE CRUISE

HOVER APPROACH

FLIGHT CONTROLS

- MULTIMODE SCAS

- INTEGRATED
  PILOT CONTROLS
  AND DISPLAYS

REDUCED
PILOT
WORKLOAD

ORDNANCE DELIVERY

INCREASED
MISSION EFFECTIVENESS
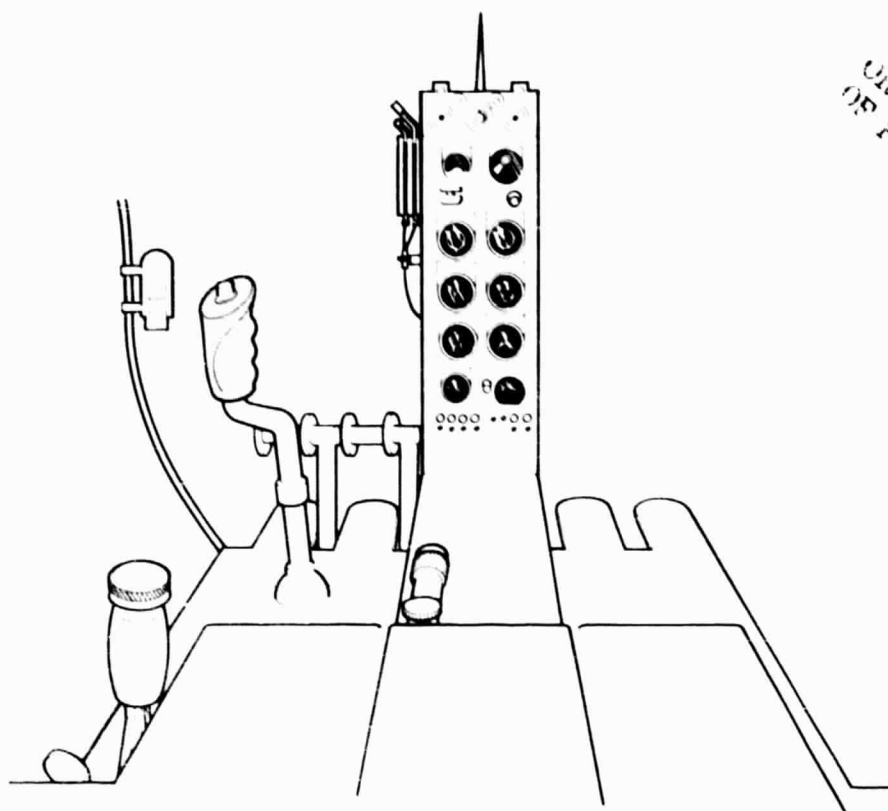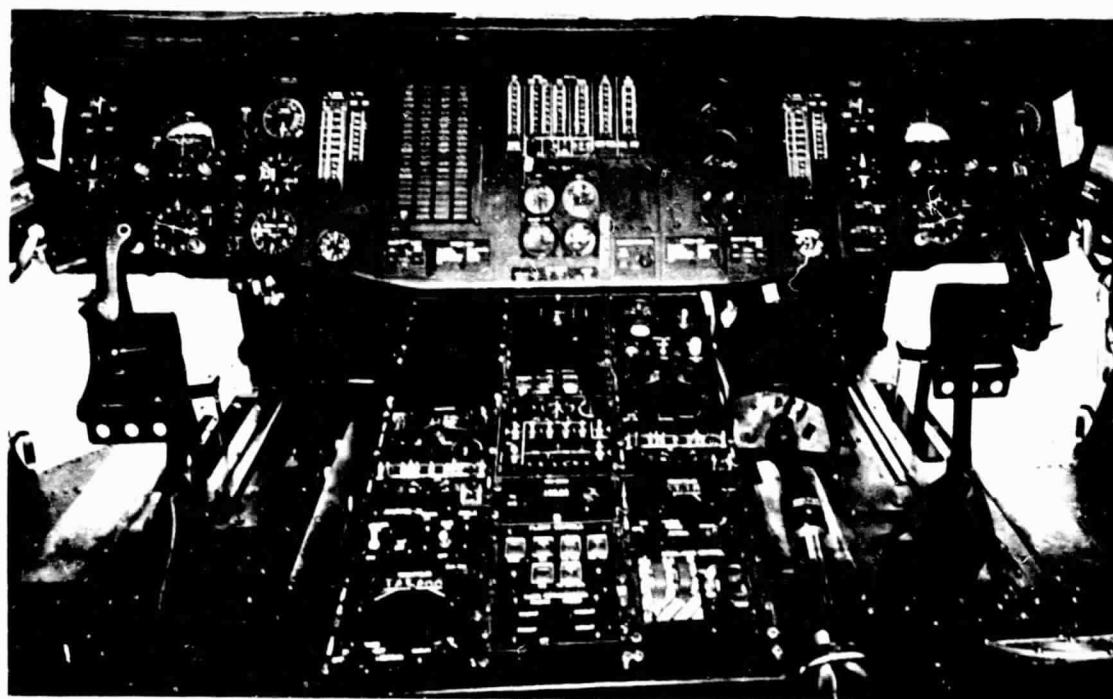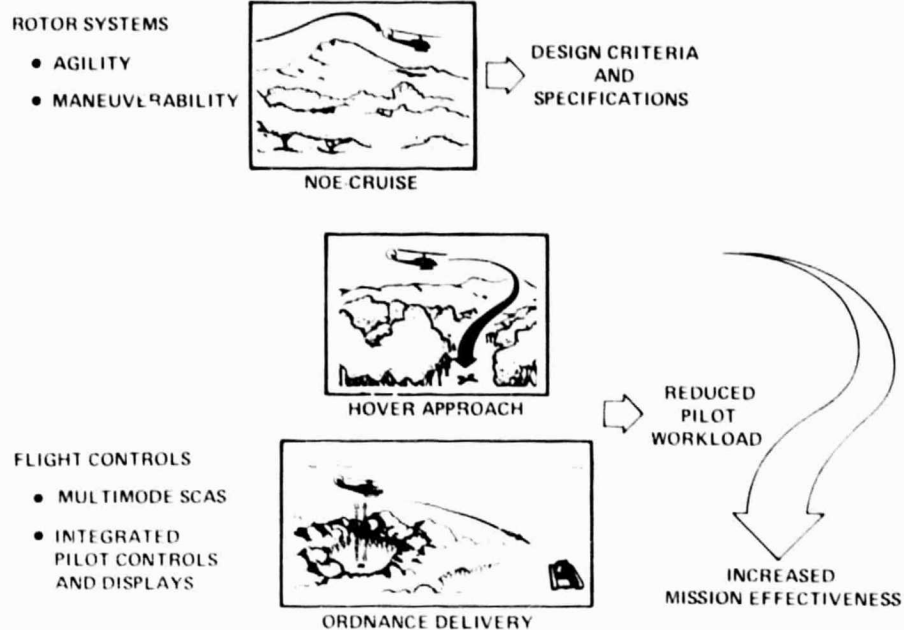
Fig. 5. Helicopter handling-qualities research.

TRADOC

DESIGN
CONCEPTS

MENS

- EVALUATE NEW ROLES/MISSIONS

- QUANTIFY MISSION DEFICIENCIES

- EVALUATE NEW TECHNOLOGY

- EVALUATE ALTERNATIVE CONCEPTS

Fig. 6. Program initiation.

**R & D**
**FLIGHT DYNAMICS**

**TRADOC SUPPORT**
**TACTICS**

Fig. 4. Threat assessment.



SSG

PM

SSEB

- FLYING QUALITIES
- COCKPIT CONTROL/DISPLAY
- STABILITY AUGMENTATION
- SYSTEMS INTEGRATION
  - NIGHT VISION
  - WEAPONS
  - NAV/GUIDE
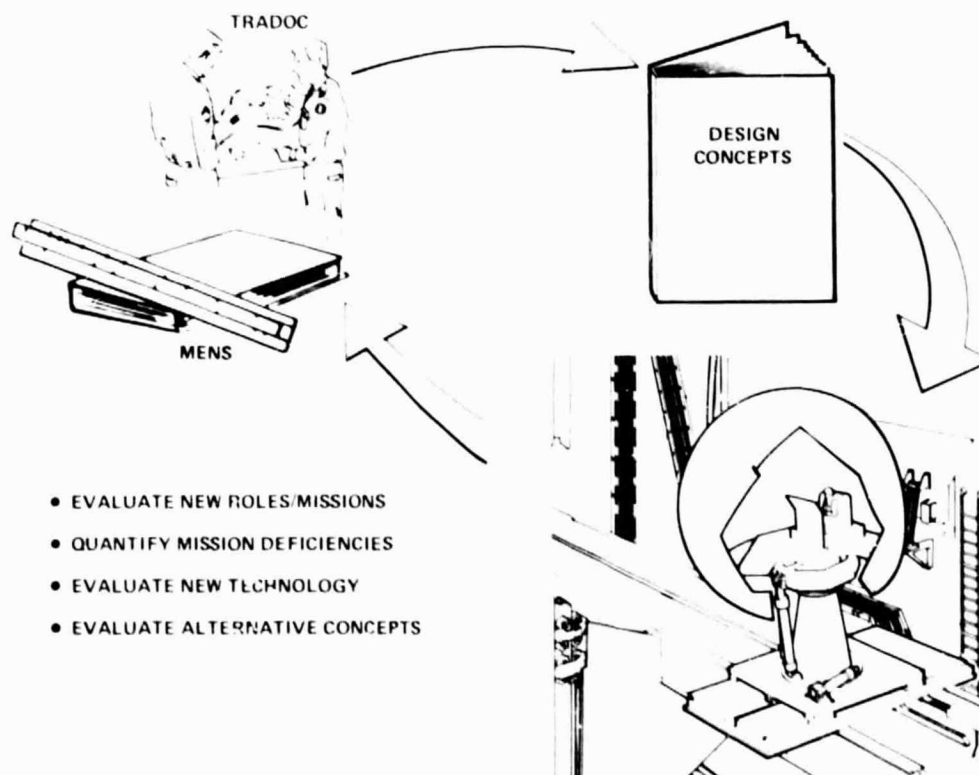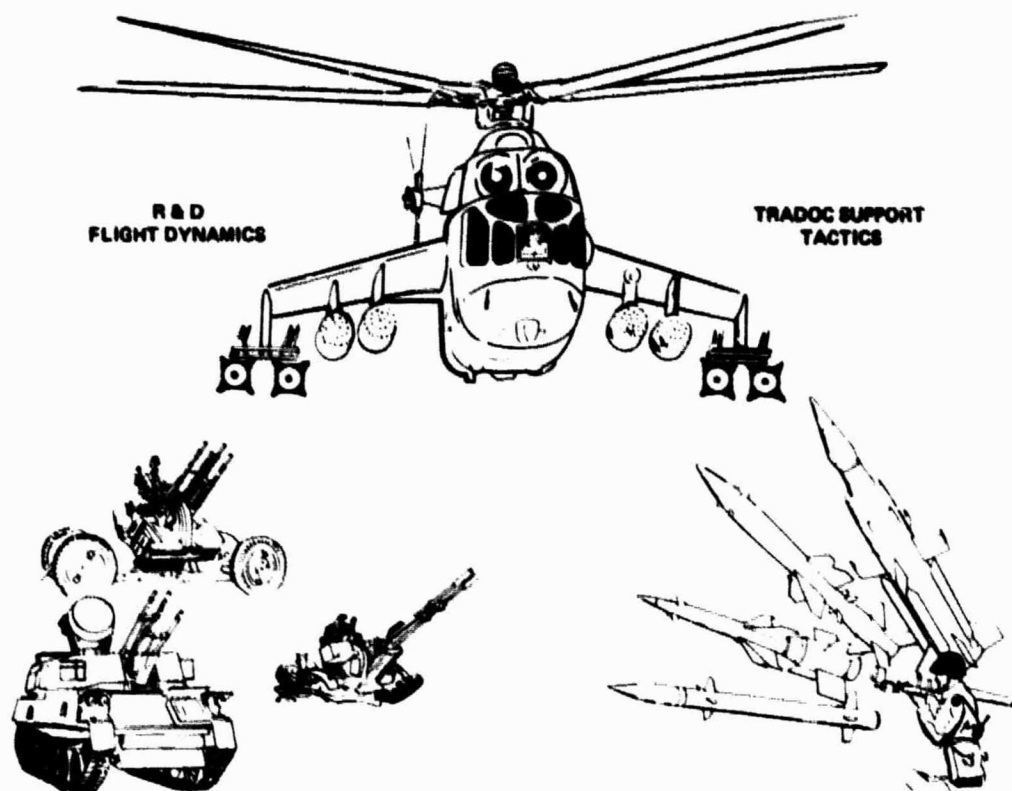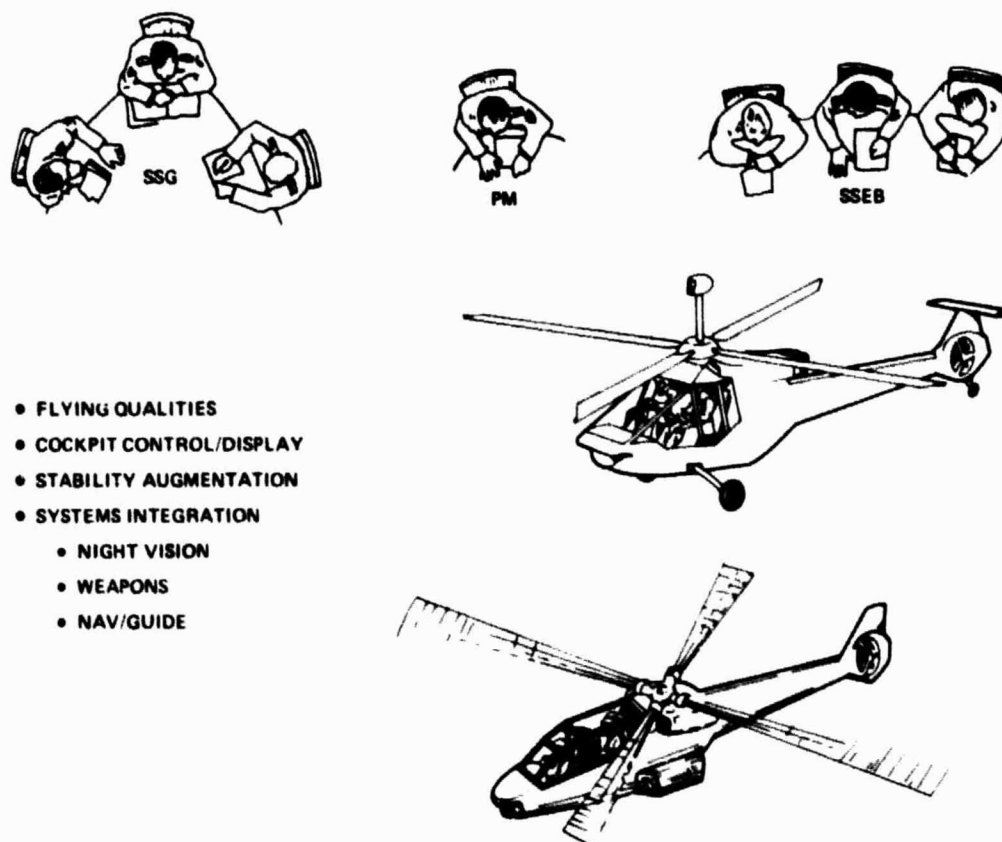
Fig. 5 Demonstration and validation.

- CONFIRM/EVALUATE FLYING QUALITIES
- INVESTIGATE FAILURE EFFECTS
- EVALUATE DANGEROUS MANEUVERS
- PLAN FLIGHT TESTING
- SYSTEMS INTEGRATION
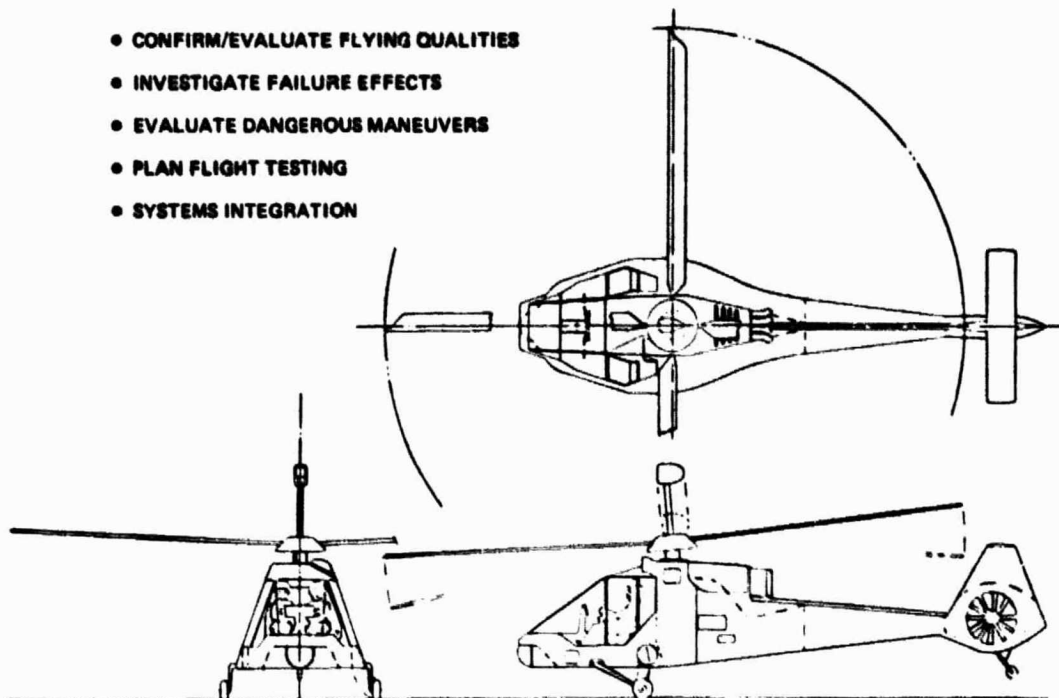
Fig. 6. Engineering development.
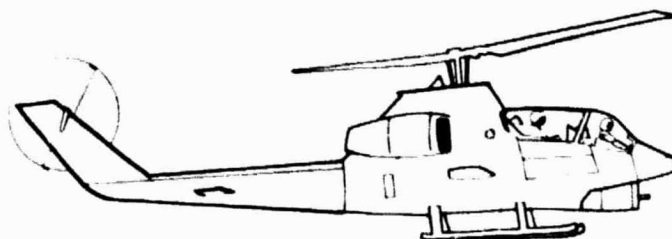
- NEW FIRE CONTROL SYSTEM
- WEAPON SWITCHING
- EXPLOIT NEW ENGINE, TRAN, BLADES
- ADVANCED AUGMENTATION SYSTEM
- NEW INTEGRATED AVIONICS SYSTEM
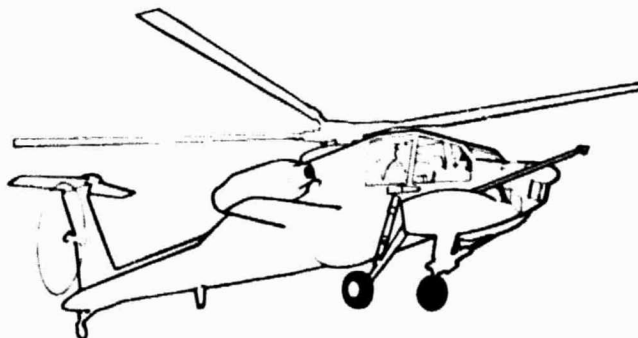
- MULTIMODE FBW
- AIR – AIR COMBAT WITH
  HUD
  AUTO FIRE CONTROL
  FORWARD-FIRING GUN
  MISSILES
- NEW CREW STATION CONFIGURATIONS

Fig. 7. Product improvement.

NOE Ⓐ   CONTOUR Ⓑ   LOW LEVEL Ⓒ
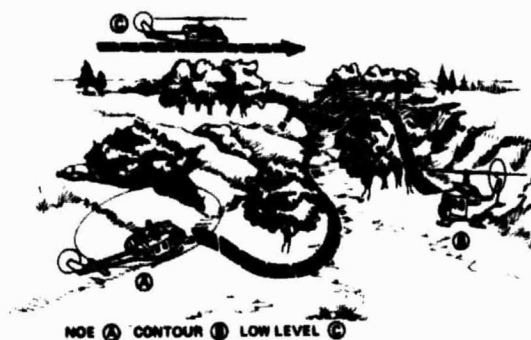
Fig. 8.   Terrain flying regimes.
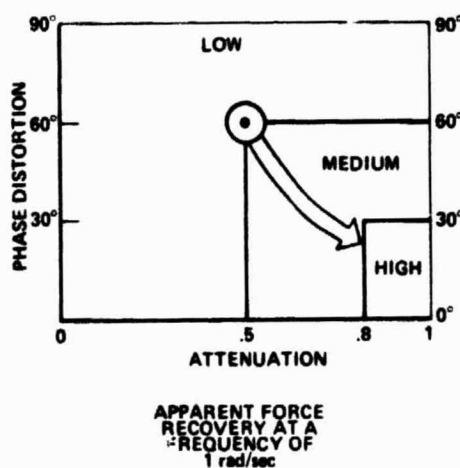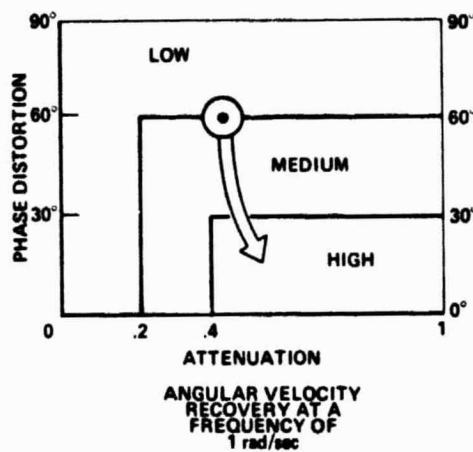


Fig. 9.   Platform motion fidelity criteria.
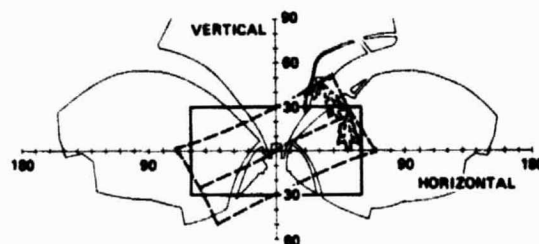


Fig. 10.   Effect of display rotation on viewing area (from AH-1G — pilot's position).



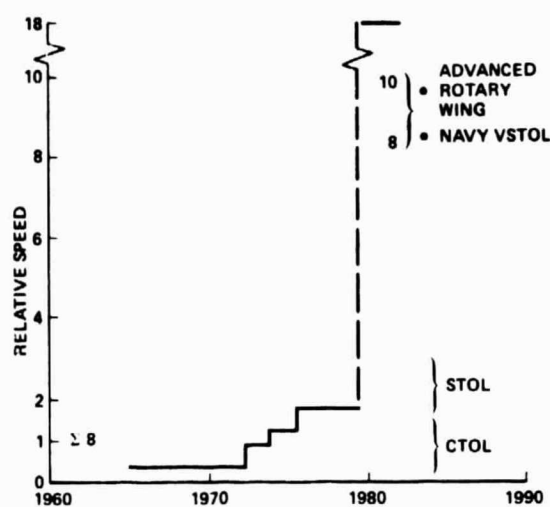NOTE: CONTRAST ≡ $\dfrac{\text{TARGET LUMINANCE} - \text{BACKGROUND LUMINANCE}}{\text{BACKGROUND LUMINANCE}}$
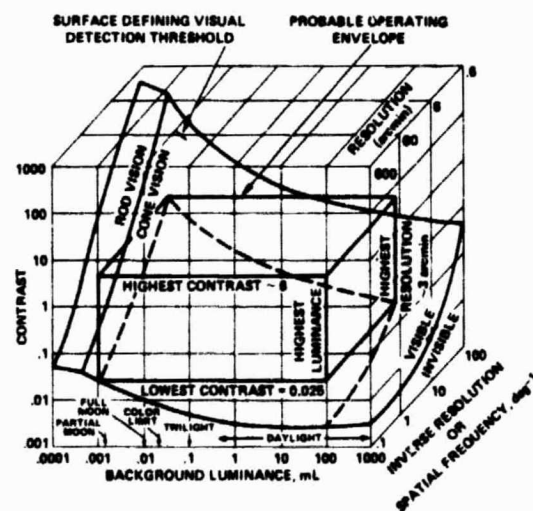
Fig. 11.   Visual performance envelope.

Fig. 12. Simulator digital computer capability and requirements.
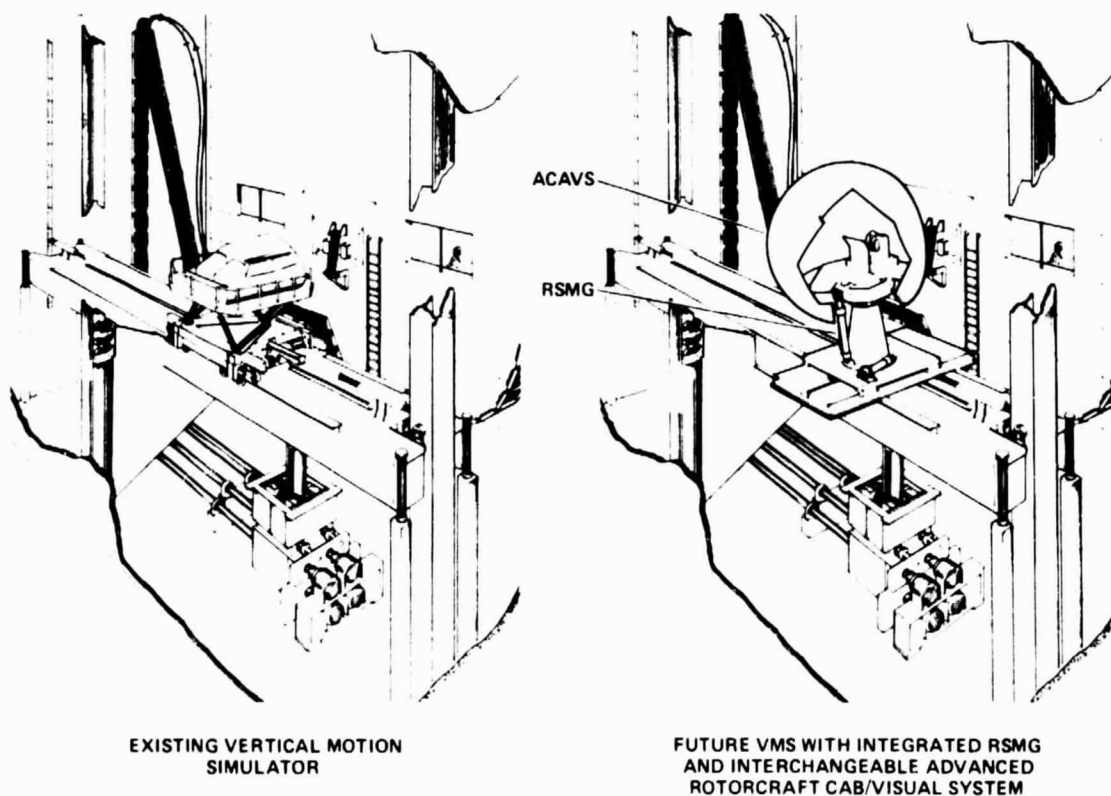


Fig. 13. Vertical Motion Simulator (VMS).



EXISTING VERTICAL MOTION
SIMULATOR

FUTURE VMS WITH INTEGRATED RSMG
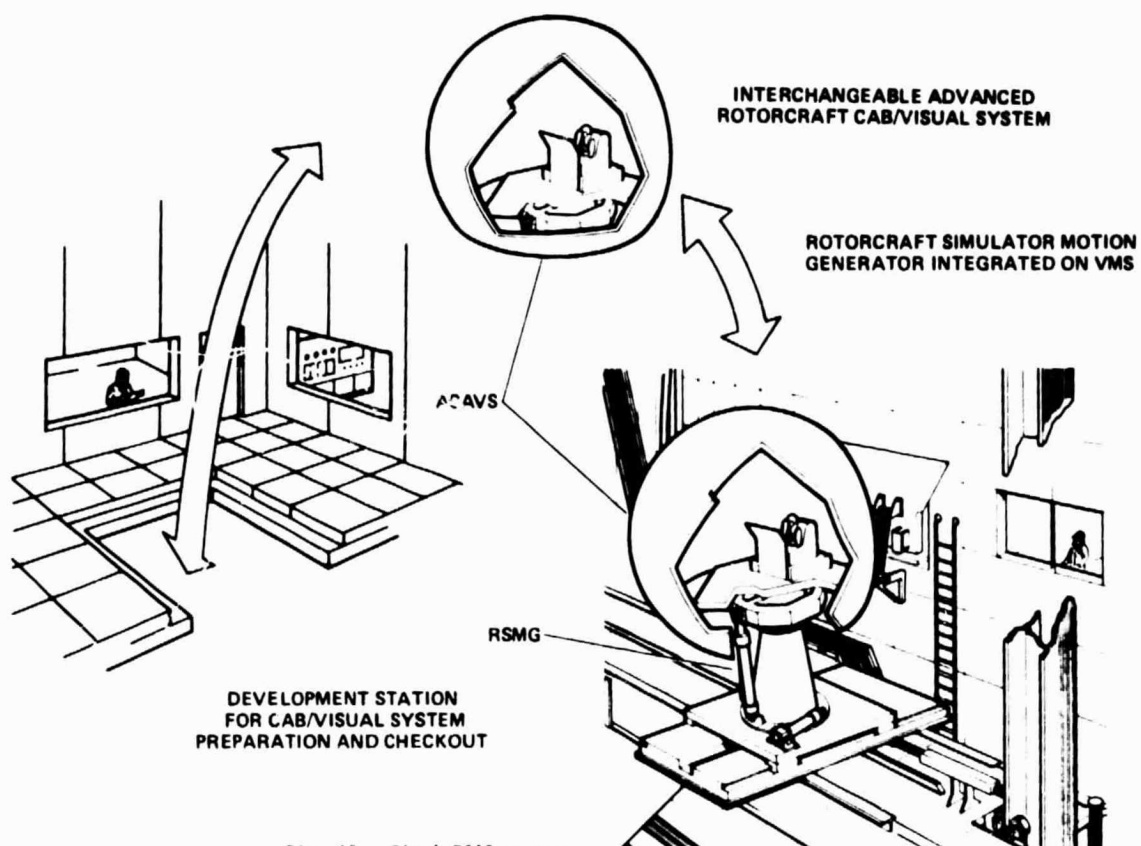AND INTERCHANGEABLE ADVANCED
ROTORCRAFT CAB/VISUAL SYSTEM
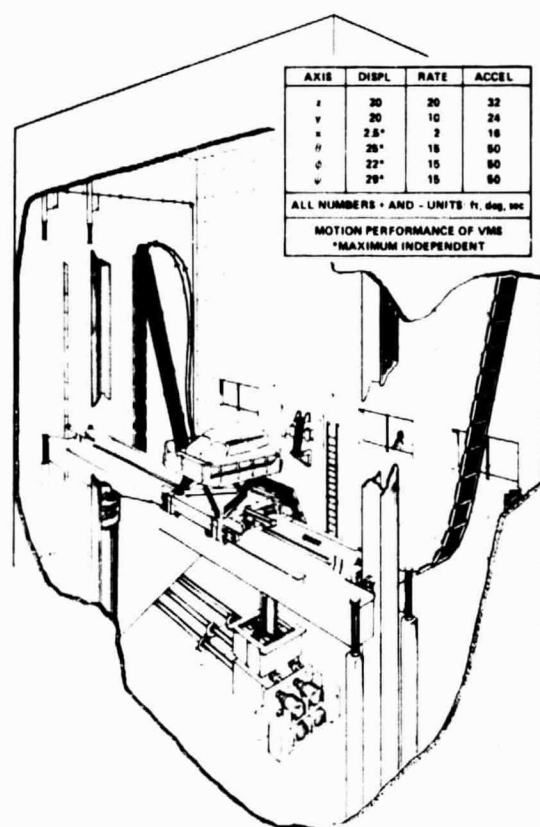
Fig. 14. Vertical Motion Simulator (VMS) RSIS project overview.

INTERCHANGEABLE ADVANCED
ROTORCRAFT CAB/VISUAL SYSTEM

ROTORCRAFT SIMULATOR MOTION
GENERATOR INTEGRATED ON VMS

ACAVS

RSMG

DEVELOPMENT STATION
FOR CAB/VISUAL SYSTEM
PREPARATION AND CHECKOUT

Fig. 15. Final RSIS system.

| PARAMETER | SYSTEM | SPEC |
|-----------|--------|------|
| RESOLUTION | 8.0 arcmin LP | 6.0 |
| FOV | 165 H × 55 V | 120 H × 60 V |
| BRIGHTNESS | 23 FL | 30 |
| CONTRAST | 45:1 | 30:1 |
| COLOR | RGB | 2 |

SYSTEM SLEWABLE FOV (TITUS L.V.)

55

55

165
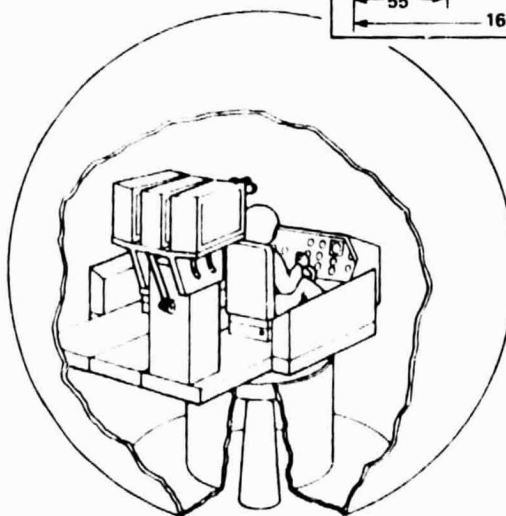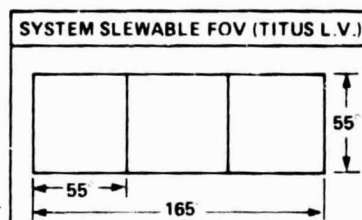
UNIQUE SYSTEM ELEMENTS
- 3 LIGHT VALVE PROJECTORS
- PROJECTOR PITCH GIMBAL
- 3 CHANNEL COMPUTER IMAGE GENERATOR
- 3 EXTENSION LENSES (PERISCOPE)
- SPHERICAL SCREEN
- PITCH HEAD TRACKER

Fig. 16. Light-valve and extension optic visual
system concept.

| PARAMETER | SYSTEM | SPEC |
|---|---|---|
| RESOLUTION | 6.5/11.5 arcmin LP | 6.0 |
| FOV | 140°H × 70°V | 120°H × 60°V |
| BRIGHTNESS | 5.3 FL | 30 |
| CONTRAST | 42:1 | 30:1 |
| COLOR | RGB | 2 |

**SYSTEM SLEWABLE FOV (TITUS L.V.)**

*HIGH-RESOLUTION INSET
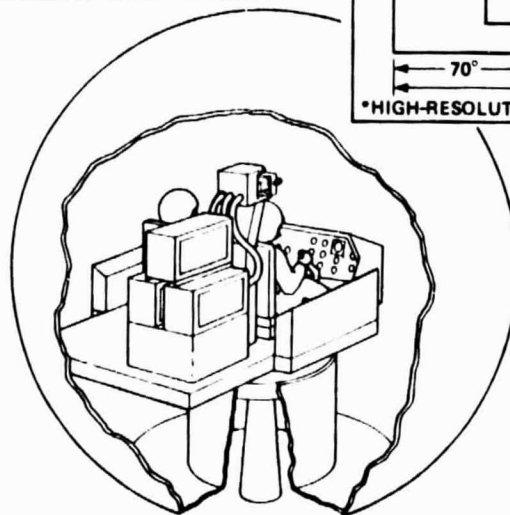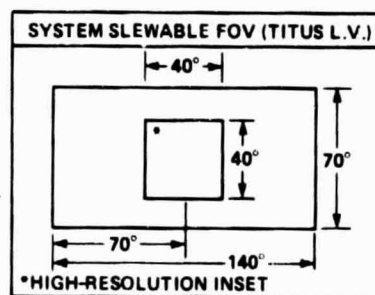
UNIQUE SYSTEM ELEMENTS:
- 3 LIGHT VALVE PROJECTORS
- 3 CHANNEL COMPUTER IMAGE GENERATOR
- PITCH/YAW GIMBAL AND OPTICS HEAD
- 3 MULTIPLEXED FIBER OPTIC BUNDLES
- SPHERICAL SCREEN

Fig. 17.  Light-valve and fiber optics visual system concept.

| PARAMETER | SYSTEM | SPEC |
|---|---|---|
| RESOLUTION | 6 arcmin LP | 6.0 |
| FOV | 175 H · 60 V | 120 H · 60 V |
| BRIGHTNESS | 5 FL | 30 |
| CONTRAST | 50:1 | 30:1 |
| COLOR | RGB | 2 |

**SYSTEM SLEWABLE FOV (LASER)**
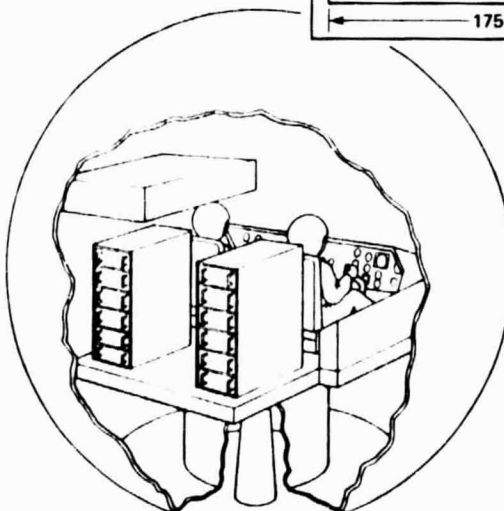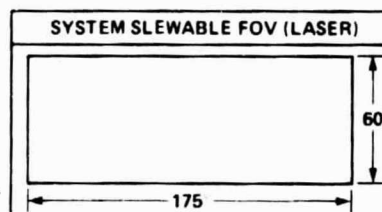
UNIQUE SYSTEM ELEMENTS:
- 2 COLOR LASER SCANNER
- PITCH GIMBAL
- SPHERICAL SCREEN
- HEAD TRACKER
- VIDEO PROCESSOR
- SUPPORT EQUIPMENT
- VACUUM/GAS SUPPLY AND WATER SUPPLY
- 6 CHANNEL COMPUTER IMAGE GENERATOR

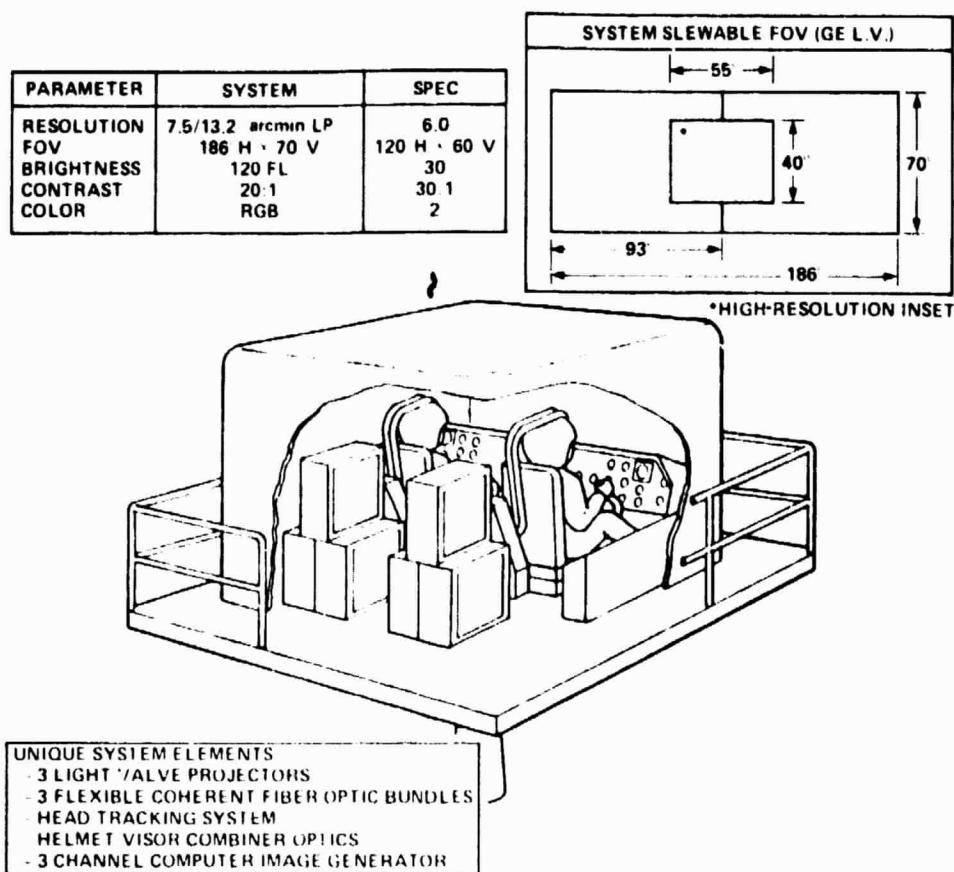Fig. 18.  Scanning laser visual system concept.

| SYSTEM SLEWABLE FOV (GE L.V.) |
|---|



*HIGH-RESOLUTION INSET

| PARAMETER | SYSTEM | SPEC |
|---|---|---|
| RESOLUTION | 7.5/13.2 arcmin LP | 6.0 |
| FOV | 186 H · 70 V | 120 H · 60 V |
| BRIGHTNESS | 120 FL | 30 |
| CONTRAST | 20:1 | 30:1 |
| COLOR | RGB | 2 |



UNIQUE SYSTEM ELEMENTS
- 3 LIGHT VALVE PROJECTORS
- 3 FLEXIBLE COHERENT FIBER OPTIC BUNDLES
- HEAD TRACKING SYSTEM
- HELMET VISOR COMBINER OPTICS
- 3 CHANNEL COMPUTER IMAGE GENERATOR

Fig. 19.  Helmet-mounted display visual system concept.



HELMET
TRANSLATION
AND ROTATION

VIRTUAL IMAGE
VISOR SCENE

CGI SCENE
WITH COCKPIT
MAPPING

COCKPIT SEE-THROUGH
AREA BLANKING

Fig. 20.  Helmet-mounted visor display blanker.