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Edwin W. Aiken, William S. Hindson, J. Victor Lebacqz, and Dallas G. Denery
Ames Research Center, Moffett Field, California

Michelle M. Eshow, Aeroflightdynamics Directorate, U.S. Army Aviation Systems Command,
Ames Research Center, Moffett Field, California

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Ames Research Center
Moffett Field, California 94035-1000

ROTORCRAFT IN-FLIGHT SIMULATION RESEARCH AT NASA AMES: A REVIEW OF THE 80s AND PLANS FOR THE 90s

Edwin W. Aiken,* William S. Hindson,** J.Victor Lebacqz,† and Dallas G. Denery‡
NASA Ames Research Center
Moffett Field, California

Michelle M. Eshow§
U.S. Army Aeroflightdynamics Directorate (AVSCOM)
Moffett Field, California

ABSTRACT

A new flight research vehicle, the Rotorcraft-Aircrew Systems Concepts Airborne Laboratory (RASCAL), is being developed by the U.S. Army and NASA at Ames Research Center. The requirements for this new facility stem from a perception of rotorcraft system technology requirements for the next decade together with operational experience with the Boeing Vertol CH-47B research helicopter that was operated as an in-flight simulator at Ames during the past 10 years. Accordingly, both the principal design features of the CH-47B variable-stability system and the flight-control and cockpit-display programs that were conducted using this aircraft at Ames are reviewed. Another U.S. Army helicopter, a Sikorsky UH-60A Black Hawk, has been selected as the baseline vehicle for the RASCAL. The research programs that influence the design of the RASCAL are summarized, and the resultant requirements for the RASCAL research system are described. These research programs include investigations of advanced, integrated control concepts for achieving high levels of agility and maneuverability, and guidance technologies, employing computer/sensor-aiding, designed to assist the pilot during low-altitude flight in conditions of limited visibility. The approach to the development of the new facility is presented and selected plans for the preliminary design of the RASCAL are described.

INTRODUCTION

Over 40 years ago, the first variable-stability aircraft in the United States was developed and operated by the National Advisory Committee for Aeronautics (NACA) Ames Aeronautical Laboratory, Moffett Field, California. This single-pilot F6F-3 aircraft with a variable-stability aileron and rudder servo system accumulated over 400 hours of research flight investigating the effects of variations in lateral-directional dynamics. Since that time, a long succession of variable-stability aircraft, including conventional, STOL, fixed-wing V/STOL, and rotorcraft configurations, has been developed at Ames to serve as research facilities for aeronautical research and development (R&D) activities.

In 1965, the U.S. Army and the National Aeronautics and Space Administration (NASA) signed an agreement for joint research participation based on a common interest in aeronautical R&D, particularly in the area of rotorcraft, and established what would eventually become the Army Aeroflightdynamics Directorate, collocated with the NASA's Ames Research Center. The presence of this Army research laboratory at Ames had a profound effect on the decision of NASA Headquarters to select Ames as the lead center for its rotorcraft R&D program in 1976. A major aspect of the NASA/Army joint agreement has been the development and operation by Ames of a series of helicopter in-flight simulators, using Army aircraft on loan to NASA, to complement and supplement its computational, wind-tunnel, and ground-simulation research facilities.[1] The first of these aircraft, the UH-1H V/STOLAND helicopter, was in use at Ames for almost 10 years, beginning in 1977, for investigations into guidance and control concepts and generic handling-qualities effects, principally during terminal area operations. The NASA/Army CH-47B helicopter (Fig. 1), described in this paper, was transferred from NASA Langley Research Center to Ames in 1979 and accumulated 450 research flight hours at Ames before its return to the Army in 1989.

During this same period, helicopter in-flight simulators were being developed and operated by government research laboratories in other nations.[1] The National Aeronautical Establishment of Canada has operated variable-stability helicopters since 1961; the most recent being a Bell 205, in operation since 1969 and logging over 3,000 flight hours. Under the auspices of a Memorandum of Understanding between the United States and Germany, NASA/Army engineers and pilots at Ames participated with their German counterparts in experiments associated with the development of the variable-stability Bo-105 Advanced Technologies Testing Helicopter System (ATTHeS) by the German Aerospace Research Establishment (DLR). Recently, the French have developed a fly-by-wire Aerospatiale Dauphin for generalized active control research.

During the planning for two new research programs at Ames in 1988—the Automated Nap-of-the-Earth Flight (ANOE) and Superaugmented Controls for Agile Maneuvering Performance (SCAMP) programs—it became clear that a research vehicle with more advanced capabilities was required to attain program objectives. An in-house study was conducted to identify the required attributes of this new vehicle and to provide a comparative evaluation of candidate aircraft. In addition to a need for substantially more

*Aerospace Engineer, RASCAL Program Manager.
**Aerospace Engineer and Pilot.
†Chief, Flight Dynamics and Control Branch.
‡Chief, Aircraft Guidance and Navigation Branch.
§Aerospace Engineer, RASCAL Project Engineer.
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inherent maneuverability and agility in the basic vehicle, the research system installed in the aircraft would have to provide a capability well beyond that of the traditional "in-flight simulator." What was required was a flexible "airborne laboratory" capable of supporting investigations of advanced rotorcraft guidance and control concepts for both civil and military mission tasks. The ANOE and SCAMP programs were both initiated at Ames in 1988. In 1989, the CH-47B helicopter was returned to the Army, and, in that same year, the Army provided a Sikorsky UH-60A Black Hawk helicopter (Fig. 2) to Ames to serve as the basis for the development of the new research vehicle: the Rotorcraft-Aircrew Systems Concepts Airborne Laboratory (RASCAL).

This paper provides a summary of the design features of the NASA/Army CH-47B variable-stability helicopter and the highlights of the research programs which it supported. It then describes the development of the requirements for the new research vehicle and summarizes the results of the in-house evaluation of candidate aircraft. Finally, the plans for the development of the RASCAL are described, including the research system design requirements, design philosophy, and the approach to be taken in its development.

CH-47B CAPABILITIES AND RESEARCH PROGRAMS

Facility Description

The NASA/Army CH-47B variable-stability helicopter (Fig. 1) was operated at Ames Research Center from 1979 to 1989, during which time it accumulated approximately 450 flight hours. Its original configuration upon transfer from NASA Langley is described in Ref. 2. Its capabilities were improved at Ames as described in Ref. 3, which also reviewed the research programs conducted on the vehicle through 1985. Those capabilities are next summarized, followed by a review of the research that was conducted from 1986-1989. The aircraft was returned to the manufacturer in October of 1989 for D-model conversion and subsequent return to the U.S. Army inventory.

A schematic of the CH-47B research system is presented in Fig. 3. The aircraft was equipped with full-authority, electrohydraulic actuators in each of the four control axes: differential collective (pitch), lateral cyclic (roll), differential lateral cyclic (yaw), and collective (heave). The research actuator motions were transmitted to the flight-control system of the basic CH-47B through electrohydraulic rotary clutches, thereby moving the safety pilot's controls. The research system was essentially a single-channel, fail/safe design in terms of sensors, computers, and actuators. Safety in the event of excessive actuator motion was guaranteed by means of in-line, triply-redundant, digital control-rate monitors. These monitors were independent of the flight computers and were set to disengage the research system whenever any control rate exceeded 50% of the full throw of the pilot's controls per second. There were also manual disengage switches at each pilot station and at an operator's console. Finally, in the event of a failure to disengage, the clutches could be slipped by the safety pilot with a moderate amount of force until a safe landing could be made. With these safety features, the research system was qualified for use up to 120 knots and for hover operations to touchdown.

The evaluation pilot cockpit was equipped with conventional controls, but the center-stick controller included a programmable artificial feel and trim system (AFTS). In addition, a right-hand, four-axis, small-displacement side-arm controller could be used in any combination with the conventional collective and pedal controllers. To support display research, a programmable Sperry Flight Systems color electronic attitude indicator was installed in the instrument panel.

Computing capability on-board the aircraft consisted of a Sperry 1819A minicomputer programmed in assembly language and, after 1986, a ruggedized Digital Equipment Corporation PDP 11/73 microcomputer that was programmed in FORTRAN. A TR-48 analog computer was available to facilitate special signal-conditioning requirements associated with sensor inputs and command outputs.

CH-47B Flight Experiments, 1986-1989

The flight experiments conducted during the last 4 years of CH-47B operation made extensive use of its capabilities that had been developed up to that time. Particular use was made of the explicit model-following control system,[4,5] which was designed for near-hover maneuvering. An extensive investigation of the effects of high-order dynamics on the bandwidth of helicopter flight control systems was also carried out.[6] The experiments included control- and display-law design[7-12] and handling-qualities investigations,[13-14] as well as use of the CH-47B as an instrumented platform.[15] The variety of study topics is illustrative of the flexibility of the CH-47B research system.

Reference 7 describes the development of a pilot-selectable automatic hover control-law. A prerequisite for that work was the generation of precise position and ground velocity signals using the available ground-based laser tracker combined with on-board Doppler radar, linear accelerometers, a radar altimeter, and an inertial navigation unit for Euler angle measurements. The linear velocity and position signals generated using these sensors were smooth, accurate, and robust to dropouts in any of the sensors. In Ref. 8, the hover-hold law was used as one of several modes in a multi-mode control-law experiment that investigated issues relating to pilot selection of control modes in realistic, divided-attention mission tasks.

The position and velocity estimates developed for those experiments were essential to three display-law design investigations performed on the aircraft and described in Refs. 9-11. Those investigations sought to determine the design goals and handling-qualities issues associated with the symbol drive laws for hovering displays such as that used in the AH-64 Apache Pilot Night Vision System. The importance of properly specified controlled-element dynamics was demonstrated, and, display-law design techniques for enhanced operational effectiveness were developed that integrated the display and vehicle dynamics, considering workload and performance. The flight experiment reported in Ref. 12 validated advanced, integrated control- and display-laws for blind vertical landings as applied to a jet VTOL fighter.

Fundamental handling-qualities data were gathered in the experiments of Refs. 13 and 14. The first investigation quantified the effects of pitch-roll cross-coupling in either the pilot controls or the aircraft angular-rate response. The second investigated the effects of center-stick controller characteristics, with an emphasis on the physical parameters that affect the controller dynamics. Both experiments made substantial contributions to the rotorcraft handling-qualities flight data base.

Finally, the experiment of Ref. 15, conducted to support the ANOE program, obtained digital video image records of terrain obstacles in low-altitude flight to be processed and compared with true aircraft and obstacle position data.

TRANSITION TO RASCAL

Although the CH-47B proved to be a versatile and productive research tool, it had limitations that prevented investigation of such critical topics as high-bandwidth flight control and agility/maneuverability. As with any digital flight-control system, the achievable bandwidth was limited by system delays and by potential destabilization of the rotor modes.[6] Most important, the actuator rate monitors, while ensuring safety and minimizing the requirements for extensive software validation and verification and for hardware redundancy, limited aggressive maneuvering by the pilot. Nuisance disengagements were a common occurrence unless the experiment and task designs were tailored to avoid them.

In the late 1980s, NASA and Army research goals were revised to include the flight validation of integrated control technologies that enhance maneuverability, agility, and mission effectiveness. These goals precipitated the search for a more suitable host helicopter. The search was completed in 1988, when the UH-60A Black Hawk helicopter was selected to be the RASCAL vehicle.

The selection was based on the evaluation of several candidate aircraft against a set of appropriate criteria. Those criteria included performance parameters such as payload and power available; airspeed, load factor, and sideslip envelopes; and handling-qualities capabilities such as control power, damping, inherent cross-coupling, linearity of response, and vibration. Other considerations included physical characteristics such as cabin volume, structural strength for cockpit modifications, operations and maintenance factors in the NASA environment, safety and crashworthiness, and available research support tools such as mathematical models. Ten vehicles were considered initially, and demonstration flights were conducted by NASA test pilots in four of the most likely candidates. Of these, the UH-60A was determined to have the advantage in most categories and, on balance, was found to be the best available choice for the Ames SCAMP and ANOE programs. In October of 1989, the JUH-60A that had been used as a demonstrator vehicle for the U.S. Army's Advanced Digital-Optical Control System (ADOCS) program was assigned to Ames as the RASCAL vehicle.

RASCAL RESEARCH PROGRAMS AND SYSTEM DESIGN REQUIREMENTS

The design requirements for the research system to be developed and integrated into the RASCAL aircraft are driven by the requirements of several major NASA and Army R&D programs that involve the utilization of RASCAL as a flight research facility. These programs include the following.

1. Superaugmented Controls for Agile Maneuvering Performance (SCAMP): Analysis, ground simulation, and flight research to investigate methods for the enhancement of rotorcraft maneuverability and agility through the application of advanced flight-control concepts

2. Automated Nap-of-the-Earth Flight (ANOE): Analysis, ground simulation, and flight research to develop low-altitude guidance algorithms and pilot display laws for rotorcraft terrain-following/terrain-avoidance and obstacle avoidance

3. Rotorcraft Agility and Pilotage Improvement Demonstration (RAPID): In-flight validation and demonstration of ground-simulation-derived solutions to selected Army-identified "technology barriers" to the development of next generation/future systems

SCAMP Requirements

The increasing use of rotorcraft in more demanding missions such as higher-speed near-terrain flight, automated NOE flight, and air combat places a premium on vehicle agility and maneuverability. The U.S. Army has made the enhancement of maneuverability and agility one of its top R&D program objectives. Limitations on agility and maneuverability are typically the result of design trade-offs in the rotor system combined with an inability to control effectively the influence of rotor dynamics on vehicle stability. To alleviate the costs of these trade-offs and to exploit additional capabilities that are prohibited by current control-system design procedures, the integration of new interrelated control strategies is required. Typically, even in state-of-the-art rotorcraft, these strategies are either not used at all, or are used with no integration with other elements of the control-design task. Reference 16, the "AeroTech 2000" report, states that "experience, tools, and criteria for multidisciplinary design of integrated controls for highly interactive elements are lacking." Therefore, the development of such tools and criteria was given a high priority in that document. In addition, this same need was reinforced by a rotorcraft industry working group—the Systems Automation and Intelligence (SAINT) working group—in its recommendations to NASA during the 1985-1987 period.

Accordingly, the goals of the SCAMP program are (1) to provide methods and criteria for integrated control design for rotorcraft and (2) to use these integrated control methods to provide significant increases in rotorcraft maneuverability and agility

To achieve these goals, the specific objectives are as follows.

1. Develop an accurate mathematical model of the UH-60 helicopter rotor modes, airframe, drive train, and power plant including all interactions; and validate the model with UH-60 flight data from the RASCAL and other sources

2. Design, and evaluate in ground simulation, incrementally integrated high-bandwidth inner loop controls, rotor-state controls, propulsion/flight controls, higher harmonic controls, and flight-envelope-enhancing controls and displays

3. Validate the simulation results using piloted evaluations conducted in the RASCAL

The approach to be taken includes a progressive buildup of integration methods leading to flight evaluations in the RASCAL for each phase of the buildup.

These research goals and objectives have major implications for the design of the RASCAL research system. To support the SCAMP program, the RASCAL research system must include the following.

1. A high-quality instrumentation, signal-conditioning, and data-acquisition system, including rigid-body, rotor-state, and propulsion-system sensors suitable for experimental data and flight-control applications

2. A programmable, fly-by-wire research flight-control system including high-performance actuators; a flight-control computer, programmable in a higher-order language, with a hardware/software architecture necessary for the throughput and speed requirements of the various control concepts; and a high-speed data bus with sufficient capacity for the anticipated bus traffic

3. The capability to evaluate both conventional controllers, using an artificial force-feel system, and integrated, multi-axis side-stick controllers

4. A programmable digital engine control system

5. A flexible, programmable cockpit display system

6. An in-flight researcher interface with the system for monitoring the experiments and for effecting configuration changes to allow productive use of the available flight time

7. A ground-based development facility to allow software checkout before its implementation in flight

ANOE Requirements

The ANOE program is focused on the development of technologies for enhancing piloted low-altitude flight-path management through means of computer and sensor aiding. A lack of the technology required for computer-aided NOE flight was clearly identified in the early stages of the U.S. Army's RAH-66 Comanche development program. This deficiency led to a recommendation of the NASA Research and Technology Advisory Committee in 1985 for NASA to initiate a basic research program in this area. The research objectives were further refined through a series of SAINT working group meetings through 1987. The long-term objective of ANOE is to achieve levels of automation for aiding the pilot in NOE flight and includes a flight demonstration of the resulting computer/sensor aiding concepts.

ANOE includes two elements which will be investigated in separate flight research activities, integrated, and eventually coupled with the RASCAL research flight-control system. They are (1) pilot-directed guidance/control concepts and (2) vision-based obstacle/hazard detection.

The first of these elements will result in the development of a highly intelligent path-control capability to aid the pilot in terrain-following and, eventually, NOE flight . Two basic control modes will be developed: fully autonomous and autonomous with the capability for pilot direction. Reference 17 describes a piloted simulation program which was conducted as part of this program element to evaluate a trajectory-generation algorithm and pilot's display for low-altitude flight. The second element of the ANOE program involves the development of real-time image sensor processing techniques and motion-estimation algorithms to allow NOE navigation and obstacle detection using on-board passive and active sensors. Reference 18 provides an analysis of the problem to be solved during this element. Integration of the results of this element with those of the first element of the program will yield the obstacle-avoidance capability required for automated NOE flight.

In order to provide the capability required for the in-flight development, evaluation, and demonstration of ANOE concepts, the RASCAL research system must include the following.

1. A functional research flight-control system programmed with SCAMP control laws suitable for low-altitude flight

2. An on-board precision navigation system suitable for low-altitude flight

3. Appropriate passive (e.g., TV or FLIR) and active (e.g., radar or laser) sensors for image-based guidance and navigation including obstacle detection/avoidance

4. On-board computational capability for real-time image processing, vehicle motion estimation, guidance algorithm generation, and pilot's display generation

5. Terrain data-base storage for low-altitude navigation with no image sensor-aiding

6. A flexible, programmable pilot's display system including a digital map display and a helmet-mounted presentation of guidance commands and sensor-based imagery

7. A capability for the integration of the autonomous guidance commands with the research flight-control system

8. An instrumentation and data-acquisition system to provide a complete determination of ANOE system performance during both local and remote site operations

9. An on-board researcher's station for monitoring and controlling piloted evaluations

RAPID Requirements

Four technical elements are included under the U.S. Army's RAPID program:

1. Agility/Maneuverability: the development of rotorcraft agility/maneuverability assessment techniques, specifications, and stability and control augmentation system (SCAS) designs to enhance agility and maneuverability for a modern rotor system

2. Carefree Maneuvering: the development of control/display techniques to allow the pilot to make maximum use of the inherent vehicle capability with a minimum of added workload

3. Integrated Flight/Fire Control: investigations of improvements in weapon system effectiveness for air-to-air or air-to-ground combat which may result from including a fire-control mode in the SCAS control laws

4. Slung-Load Operations: the development of control and display laws suitable for the stabilization and control of a suspended load conducted day or night in adverse weather conditions

RASCAL research system requirements to support this Army program include the following.

1. The SCAMP research system

2. An on-board computational capability for additional control and display laws, including maneuver-envelope limiting and cueing, integrated fire and flight control, and slung-load control modes

3. An extension of the RASCAL in-flight simulation software to include simulated air-to-air and air-to-ground combat with a fire-control and weapon system, and slung-load operations

RASCAL Summary

Figure 4 provides a pictorial summary of the major component requirements for the RASCAL research system. The succeeding sections of this paper describe the approach to be taken during the initial development effort and the system architecture design philosophy, including system performance and flight safety issues.

RASCAL RESEARCH SYSTEM DEVELOPMENT STRATEGY

The buildup of the RASCAL research facility will occur in phases that correspond to the requirements of the major R&D programs which it supports. At the end of each succeeding phase of development, the RASCAL will possess a full capability for conducting flight research programs to support specific elements of each program. Table 1 provides a summary of the development phases planned for the RASCAL and the resultant research capabilities at the end of each phase.

RASCAL FLIGHT-CONTROL SYSTEM DESIGN

This section discusses the RASCAL design philosophy, design and safety goals, and general system architecture as they relate to the flight-control system development through the end of Phase I.

Definition of Design Goals

In addition to serving as the platform for the SCAMP, ANOE, and RAPID research programs, specific design goals for the flight-control system require achieving the agility and handling standards defined by ADS-33C (Ref. 19). This requirement will demand the minimization of phase lags from all system components, ranging from the conditioning of sensor signals, to computer cycle time and actuator response. In addition, the incorporation of rotor-state feedback is envisaged to enable the UH-60 to achieve the flight-control system bandwidth requirements of ADS-33C, and to demonstrate the potential of this technology.

To categorize the design and mission goals, a set of performance capability objectives has been established that embody both maneuver aggressiveness and operating environment. These performance capability objectives range from precision landing and hover tasks through aggressive hover maneuvering (as defined by the maneuvers listed in ADS-33C) to air combat and NOE flight tasks at various altitudes. The more ambitious the performance objective, the more stringent the system design requirements from a safety and reliability point of view.

Configuration studies began formally in 1989 with the study reported in Ref. 20. Two piloted simulations have also been conducted. The objective of these efforts has been to determine specifications for the research system, principally the performance of the fly-by-wire research actuators and trip thresholds associated with monitors for hardovers and other unexpected transients that are both critical elements of system design.

Design and Safety Philosophy

The distinguishing feature of this type of fly-by-wire research aircraft is the retention of the basic mechanical control system, connected in parallel and monitored assiduously by the safety pilot. This continuous readiness to resume control constitutes a fail-safe design philosophy which can permit significant savings in system complexity over fail-operate concepts. The design challenge is to exploit this potential for simplicity without compromising either safety-of-flight or mission envelope.

However, the key to achieving an acceptable fail-safe design lies in implementing highly effective and reliable fault prevention, detection, and isolation, particularly for failure modes that can result in the generation of hardover or other unexpected transients in the fly-by-wire flight control system. Several approaches are being employed simultaneously to guard against such events: component reliability, distributed redundancy, and extensive internal monitoring.

Even after system hardware has been designed and integrated in a manner that analytically achieves the desired levels of reliability, there remains the critical issue of research software. Rather than striving, at prohibitive expense, to achieve the goal of extreme reliability for the research software, an alternative approach involving risk reduction is being considered. For example, certain test conditions may require that operating altitudes be restricted or that maneuver aggressiveness be limited. In the following, the basic system architecture is outlined, some of the monitoring concepts are discussed, and an approach to the research software is presented.

System Architecture

Sensors

Figure 5 illustrates the hardware integration of sensor, computer, and actuation elements required for fly-by-wire control. Critical elements such as the inertial measuring unit (used mainly as the source of basic strapdown data), the flight-control computer (FCC), critical data pathways, and the servo control unit (SCU) are of U.S. military-standard quality and reliability. Where deemed important from a failure-probability or failure-effects point of view, sensors and other components are duplicated and their outputs comparison-tested to permit the earliest possible and most source-specific identification and isolation of system malfunctions. For example, dual-redundant radar altimeters may be included to allow more reliable determination of signal dropout and recovery. Alternatively, the inherent reliability and extensive self-monitoring of the fundamental angular rate and linear acceleration data from the ring-laser-gyro inertial unit may be considered sufficient to preclude redundancy. The precise mix of dual and simplex sensors, interfaces, and flight-control computers is yet to be defined.

A particular task of the SCAMP research programs is the investigation of rotor-state feedback to provide the necessary stability margin for high-bandwidth superaugmented flight control. Although not a Phase I requirement, various means of measuring the rotor flapping-angle and the blade lead-lag positions are being investigated to meet this requirement.

Computation

The high-performance flight-control systems that are the focus of the SCAMP research will require more computational power than has been available in the past for research rotorcraft. The algorithms associated with high-bandwidth SCAMP flight control must cycle quickly, significant signal conditioning must be employed to achieve minimum phase lag in sensor signals used in the feedback control loops, and complex mathematical models will be required in any applications of the aircraft as an in-flight simulator. In addition, SCAMP control laws will be required throughout the full flight-envelope. The design goal for control-law cycle time is 5 msec.

Currently, a likely candidate for the flight-control computer is a multiprocessor environment employing VME and VSB bus architecture and the latest military-qualified microprocessors. This architecture is widely supported with both commercial and military standard hardware and software, permitting cost-effective ground-development and flight facilities. A structured software approach, using a programming language such as C or Ada, is planned. To manage tasking and timing control in the flight environment, several commercially available real-time operating systems are being evaluated. An in-house laboratory evaluation of the capabilities and limitations of a particular hardware/software combination is in progress.

To support the initial display processing requirements of the ANOE and RAPID programs, a ruggedized high-capacity commercial graphics processor will be integrated with the FCC. This computer will be host to non-flight-critical guidance and display algorithms.

Actuation Systems

The full-authority electrohydraulic parallel actuators are the critical elements in the design. To avoid unacceptable effects of hysteresis and lost motion in precisely controlling the swashplate, they are to be located downstream of the UH-60A's mechanical mixing box. They will be mounted on a bridge structure allowing them, when engaged, to drive the input linkages of the UH-60A primary actuators. Because of the high linkage gains at this point, faults that reach the research actuators can have a very significant effect on the safety pilot's controls and on vehicle response. In addition, in order to exploit the full potential of the UH-60, actuator rates and bandwidths are very high, matching the capabilities of the primary swashplate actuators of the basic UH-60. Consequently, their action must be monitored very closely and with extreme reliability.

Although these actuators will very likely be powered by the UH-60 backup hydraulic supply, they are essentially independent of the basic UH-60A flight-control system. Consequently, the benefit to flight safety of redundant pushrods or hydraulic supplies is debatable. However, extensive monitoring of the servo, its control valves, and the associated servo-loop hardware will be used in the SCU, which itself, along with each actuator and the associated engage- and disengage-hardware, must be a highly reliable device meeting rigorous design standards. Presently, the SCU is envisaged as a hybrid computer, incorporating analog loop-closure circuits, very high-speed digital monitors, and logic controlling the engagement and hydraulic bypassing of the research actuators.

Hardover Protection Monitors

While monitoring and comparison testing will be conducted at all levels within the system architecture, an important design feature will be the incorporation in the SCU of additional monitoring to block unacceptable command signals that may reach or occur at the research actuators. To investigate the performance requirements for these final system monitors, and to evaluate different monitor design concepts, two piloted simulations were conducted in the Vertical Motion Simulator at Ames Research Center. The first simulation determined that a fault that resulted in a large full-authority step command to an actuator had to be detected and isolated within 100 msec. The pilot rating scale described in Ref. 21 was developed especially to describe the effects of these failures and the pilot's ability to recover from them, thereby providing data to define the performance requirements for the hardover protection monitors.

The second simulation identified in more detail the magnitude of sharp command signals that might be generated in the system architecture. The largest step input, and the longest duration maximum-rate command to the actuator deemed acceptable by the pilot, were determined in order to better define the trip thresholds for the hardover protection monitors. Different categories of maneuvers and different operating environments (obstacles and terrain clearance factors) were investigated. Fast digital monitors that operated on the servo-loop error signal and also on the actuator rate were designed to trip at these thresholds. These monitors were then evaluated for their susceptibility to nuisance trips in maneuvers representative of the performance category being investigated. The results of these simulations provide the basis for performance specifications for the monitor section of the SCU.

System Software

Because of the paramount importance of software in achieving the RASCAL design and mission goals, major emphasis is being placed on methods for ensuring maximum feasible reliability in areas of both systems and applications.

Once the research system hardware has been designed, integrated, and flight-qualified, software validation and verification becomes the primary long-term focus of system reliability. In the research environment, where software flexibility and productivity are crucial to research effectiveness, some fault-tolerant software methods that may otherwise be fruitful approaches to improved reliability, such as redundant and dissimilar software, are impractical. Independent specification of control laws and completely separate implementation with different languages is inappropriate to the fundamental goals of a research facility. Instead, thorough module testing, maximum practical use of validation and verification methods, and conservative flight-test procedures will be employed which together will provide the necessary levels of reliability and risk reduction.

CONCLUDING REMARKS

The genesis of a modern rotorcraft in-flight simulator at Ames Research Center has been described. Although the design requirements for this flight research facility emanate from the specific need to support several major NASA and U.S. Army research and development programs, it is clear that the long-term role of the Rotorcraft-Aircrew Systems Concepts Airborne Laboratory (RASCAL) will be as a flexible flight research facility tailored to the needs of projected future research user requirements. The RASCAL will have the potential to support future programs designed to deal with evolving and new rotorcraft mission tasks, the rapid advancements in rotorcraft guidance and control technologies, and the need to develop guidelines and criteria for the integration of these technologies in a manner that enhances the ability of the pilot to conduct an effective mission.

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TABLE 1 RASCAL RESEARCH SYSTEM DEVELOPMENT APPROACH AND CAPABILITIES

	PHASE 0 Instrumentation/Data System 1990-1991	PHASE I High Bandwidth Controls/Low-Altitude Guidance 1991-1995	PHASE II Rotor State Control/NOE Guidance 1995-1996	PHASE III Integrated Flight/Propulsion Controls 1996-1997	PHASE IV Higher Harmonic Controls (HHC) 1997-2000
			Development Approach		
Instrumentation	Standard rigid body sensors Inertial navigation unit Stereo TV sensors	Precision navigation system Rotor flap/lag angles Angular acceleration Rotor rpm Telemetry data system Integrated stereo TV/FLIR sensors	Laser/radar sensor	Engine parameters	HHC sensors
Flight Computers	On-board data acquisition system Research interface	Research flight control computers Guidance & navigation computer Display Image/graphics generator Real-time image processor Researcher's station	Rotor-state feedback and control	Programmable engine control processor	HHC processor
Flight Controls	Basic UH-60	Programmable, fly-by-wire system High-performance research actuators High-speed data bus Force feel system Side-stick controllers	Phase I	Digital engine control	HHC actuators
Displays	Basic UH-60	Advanced helmet-mounted display system Color panel-mounted displays Digital map display	Phase I	Phase I	Phase I
			Research Program Support		
ANOE	Image sensor data collection	Low-altitude flight guidance evaluations: Terrain data base Passive sensors Real-time image processor Terrain-following/avoidance guidance Helmet-mounted display of guidance commands Digital map display of navigation information	NOE flight guidance evaluations: Active sensor Obstacle avoidance guidance	Integration with flight control system	
SCAMP	Vehicle modeling data Maneuverability/agility measures	SCAMP SCAS design support Evaluation task design Control/display evaluations	Rotor-state control design evaluations	Flight/propulsion control integration	Integrated HHC design evaluations
RAPID	UH-60 simulation validation Maneuverability/agility measures	SCAS design for maneuverability/agility Handling-qualities specification support Integrated fire/flight control modes Carefree maneuvering controls/displays	Enhanced bandwidth SCAS	Slung-load SCAS design evaluations	

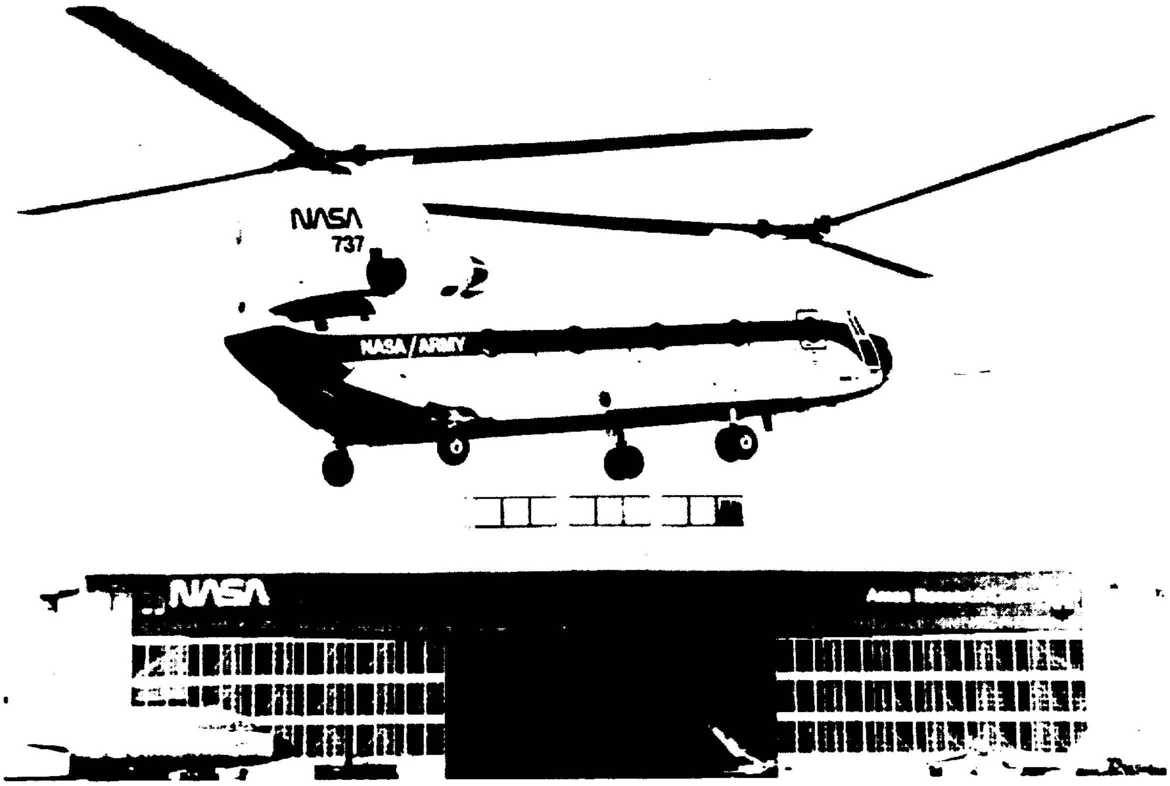

Figure 1. NASA/Army CH-47B Variable Stability Research Helicopter

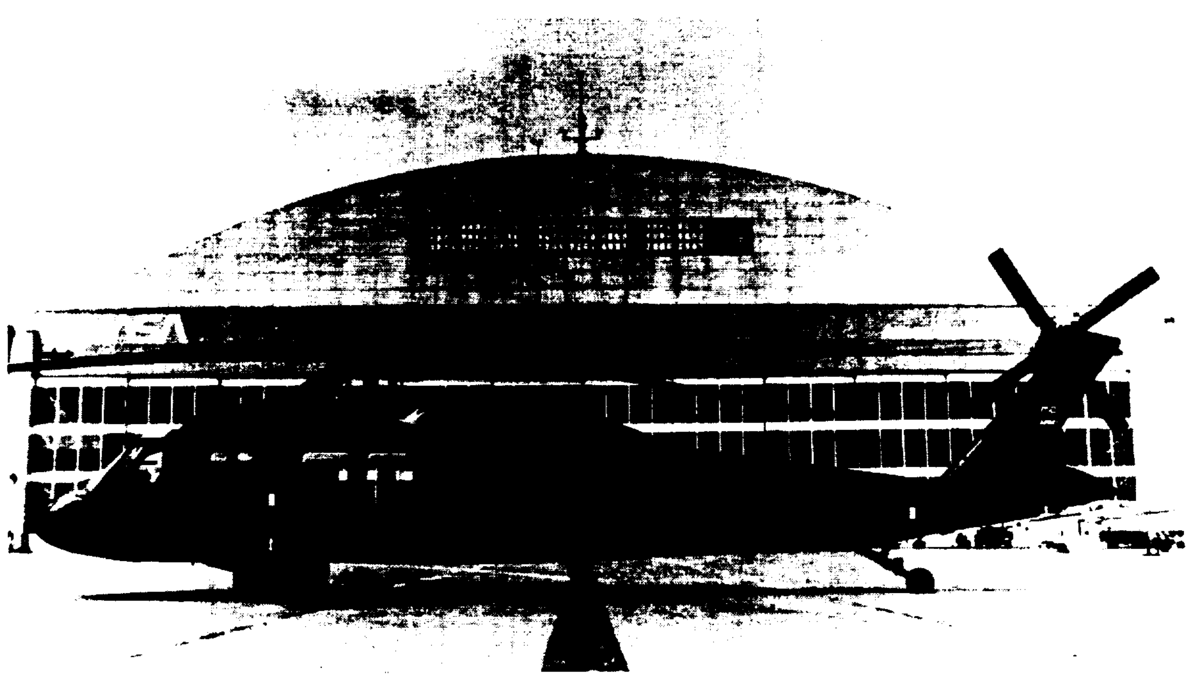

Figure 2. Rotorcraft-Aircrew Systems Concepts Airborne Laboratory (RASCAL)

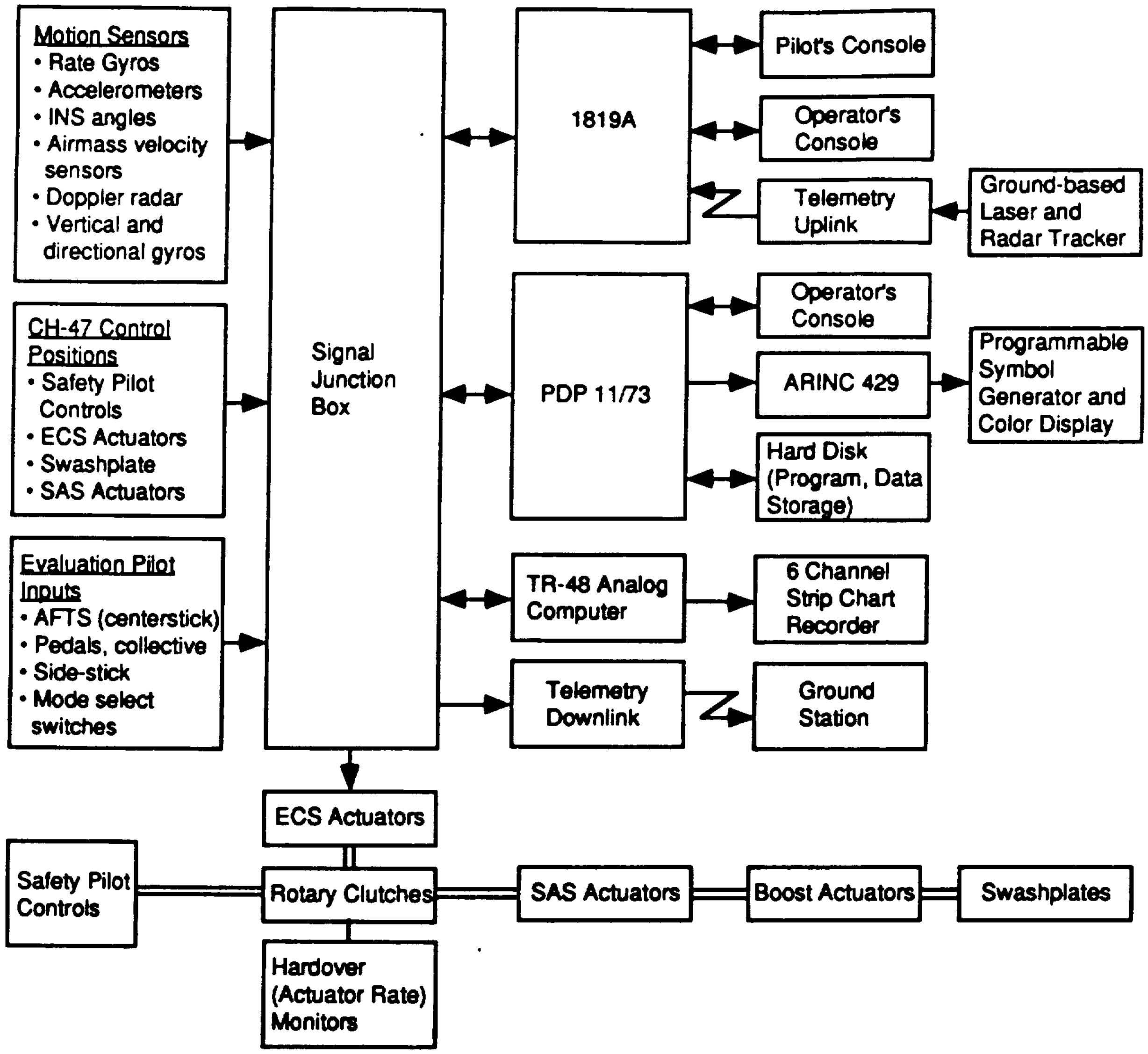

Figure 3. Schematic of CH-47 Research System

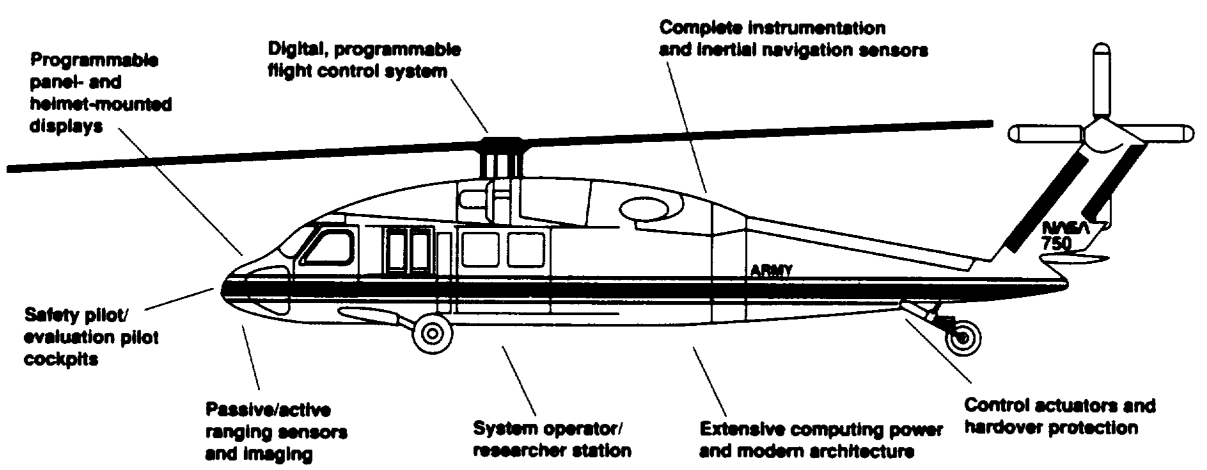

Figure 4. RASCAL Research System Components

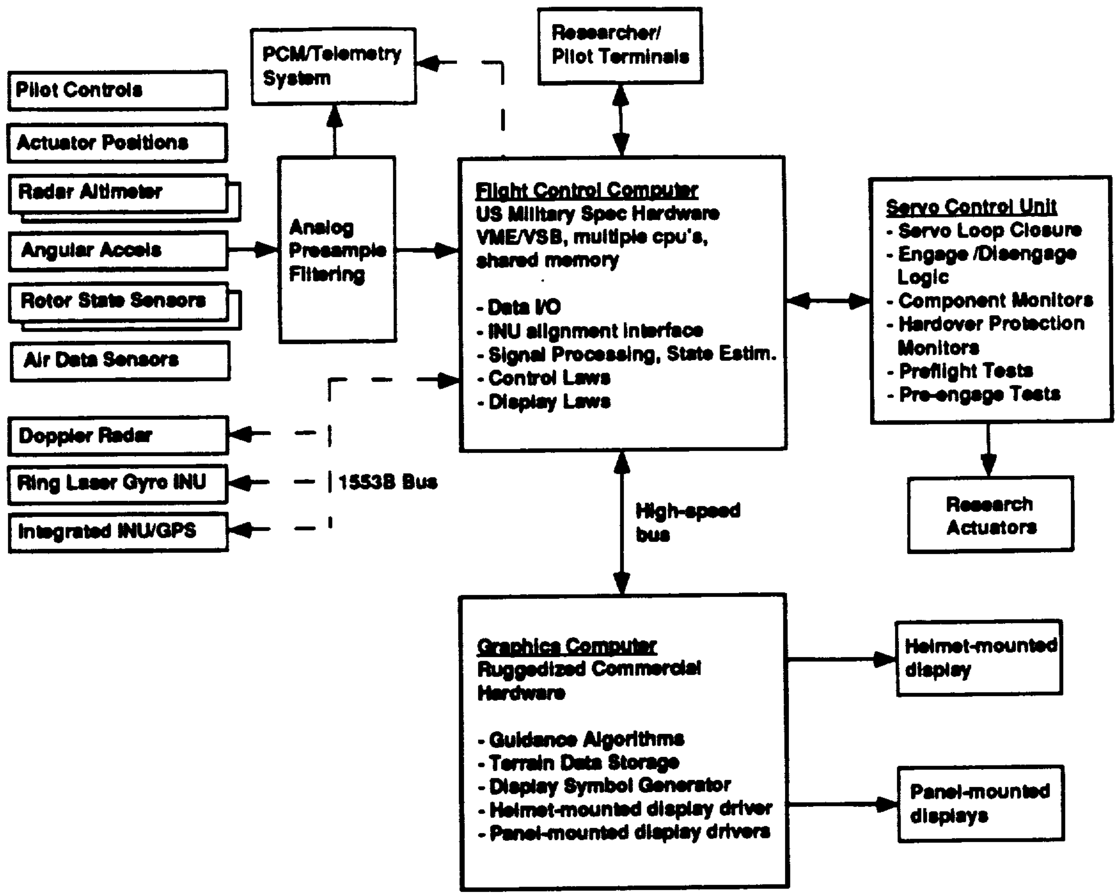

Figure 5. Proposed RASCAL Research System Architecture

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Edwin W. Aiken, William S. Hindson, J. Victor Lebacqz, Dallas G. Denery, and Michelle M. Eshow*

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Ames Research Center, Moffett Field, CA 94035-1000 and
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13. ABSTRACT *(Maximum 200 words)*

A new flight research vehicle, the Rotorcraft-Aircrew Systems Concepts Airborne Laboratory (RASCAL), is being developed by the U.S. Army and NASA at Ames Research Center. The requirements for this new facility stem from a perception of rotorcraft system technology requirements for the next decade together with operational experience with the Boeing Vertol CH-47B research helicopter that was operated as an in-flight simulator at Ames during the past 10 years. Accordingly, both the principal design features of the CH-47B variable-stability system and the flight-control and cockpit-display programs that were conducted using this aircraft at Ames are reviewed. Another U.S. Army helicopter, a Sikorsky UH-60A Black Hawk, has been selected as the baseline vehicle for the RASCAL. The research programs that influence the design of the RASCAL are summarized, and the resultant requirements for the RASCAL research system are described. These research programs include investigations of advanced, integrated control concepts for achieving high levels of agility and maneuverability, and guidance technologies, employing computer/sensor-aiding, designed to assist the pilot during low-altitude flight in conditions of limited visibility. The approach to the development of the new facility is presented and selected plans for the preliminary design of the RASCAL are described.

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