NASA Technical Memorandum 108837

Design and Flight Evaluation of an Integrated Navigation and Near-Terrain Helicopter Guidance System for Night-time and Adverse Weather Operations

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August 1994

National Aeronautics and
Space Administration

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Summary

NASA and the U.S. Army have designed, developed, and flight evaluated a Computer Aiding for Low-Altitude Helicopter Flight (CALAHF) guidance system. This system provides guidance to the pilot for near-terrain covert helicopter operations. It automates the processing of precision navigation information, helicopter mission requirements, and terrain flight guidance. The automation is presented to the pilot through symbology on a helmet-mounted display. The symbology is a "pilot-centered" design which preserves pilot flexibility and authority over the CALAHF system's automation. An extensive flight evaluation of the system has been conducted using the U.S. Army's NUH-60 STAR (Systems Testbed for Avionics Research) research helicopter. The evaluations were flown over a multiwaypoint helicopter mission in rugged mountainous terrain, at terrain clearance altitudes from 300 to 125 ft and airspeeds from 40 to 110 knots. The results of these evaluations showed that the pilots could precisely follow the automation symbology while maintaining a high degree of situational awareness.

1. Introduction

The complexity of rotorcraft missions that operate in threat areas close to the terrain at night or in adverse weather conditions for long periods of time results in high pilot workload. In order to allow a pilot more time to perform mission-oriented tasks, some type of automated system capable of performing navigation, guidance, and near-terrain flight control is needed. Automation of these tasks in a synergistic fashion is extremely challenging because of the technological advances necessary in the areas of near-terrain flight guidance and control, obstacle detection, and obstacle avoidance. NASA and the U.S. Army are currently pursuing research to develop these technologies and are performing flight evaluations of systems and concepts that have the greatest potential for improved near-terrain flight operation (ref. 1). Previous systems to facilitate flight in this environment have made use of terrain-following (TF) radar systems, forward-looking infrared (FLIR) imaging systems, night vision goggles, digital terrain maps, and integrated navigation systems (refs. 2 and 3). These systems primarily provide information to the pilot as either raw data (imagery) or derived flight director guidance. TF radar systems primarily operate in two modes. In the first mode, TF mode, flight director commands are presented to the pilot on a cockpit display commanding either fly-up or fly-down maneuvers to maintain a desired terrain clearance. The second mode provides a terrain mapping function, allowing a limited terrain avoidance (TA) capability. However, these systems do not provide integrated information for lateral and vertical maneuvering. The pilot is required to view the terrain map, choose a course to follow, switch back to the TF mode, and maneuver the helicopter to the new course while following the flight director commands for terrain clearance. The extension of TF capability to include integrated lateral and vertical maneuvering by taking advantage of on-board digital terrain maps is commonly referred to as TF/TA (ref. 4). Several TF/TA algorithms were developed by the U.S. Air Force for tactical and strategic aircraft and have been modified by NASA to suit the requirements of helicopters (refs. 5 and 6). Research at NASA Ames has produced a TF/TA algorithm along with a suitable pilot–vehicle interface for near-terrain flight evaluation. This system is called the Computer Aiding for Low-Altitude Helicopter Flight (CALAHF) guidance system (ref. 7). Its development has been aided by numerous piloted simulations which provided design feedback from pilots to engineers. These simulations also evaluated the pilot's tracking performance and situational awareness when using the system under various flight and environmental conditions. Based on the results from the simulations, the system was readied for flight evaluation using the U.S. Army's NUH-60A STAR (Systems Testbed for Avionics Research) helicopter. In preparation for the flight evaluations, additional simulations were conducted which emphasized the NUH-60 STAR specific system hardware and software and flight evaluation

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scenario (ref. 8). This paper presents a brief description of the CALAHF system, followed by a description of the system's aircraft integration and the flight evaluations.

2. CALAHF System Description

A functional block diagram of the CALAHF guidance system is shown in figure 1. The major components are the trajectory generation, guidance and display, and radar altimeter feedback algorithms along with a block representing pilot inputs and helicopter dynamics. The output from the pilot and helicopter is fed back to other system components through the aircraft's navigation and state sensors. These components are briefly described below.

2.1. Trajectory Generation Algorithm

The trajectory generation algorithm is the core of the near-terrain guidance system. It integrates mission plan information, aircraft performance characteristics, digital terrain data and precision navigation information. The mission plan consists of navigation waypoints, maximum course deviation, course heading, waypoint priority, and terrain clearance altitude. The applicable Aircraft performance characteristics are maximum climb and descent angle, maximum normal load factor, and maximum bank angle. The digital terrain data is based upon the Defense Mapping Agency's Digital Terrain Elevation Data (DMA DTED) Level I (ref. 10). With this data, and the current helicopter position and speed from the precision navigation system, the algorithm generates a near-terrain flightpath trajectory between navigation waypoints that seeks valleys within the terrain, thereby reducing exposure to enemy threats.

The trajectory generation algorithm decouples the horizontal and vertical trajectory calculation. The horizontal ground track trajectory is first determined assuming that the aircraft can fly at the desired terrain clearance altitude. The vertical trajectory is then calculated using the ground track and the digital terrain data. This procedure is shown pictorially in figure 2. The top figure shows the digital terrain in contour relief with the mission waypoints that define a course to be flown. The calculation of the trajectory begins at the aircraft's present position. Using the aircraft's current speed and discrete variations in bank angle, a tree structure of possible trajectories is calculated from the aircraft's present position to 30 sec into the future. A dynamic programming optimization is then performed over the resultant set of trajectories. The optimal trajectory is the one with the least cumulative cost. The cost is a weighted combination of mean sea level (MSL) altitude, lateral distance from the mission course between waypoints, and heading deviation from this course. A primary weighting factor is the TF/TA ratio. This ratio can vary from the 100° W TF mode to levels of TF/TA. In the TF mode, the trajectory follows precisely the mission course defined by the navigation waypoints. In TF/TA the trajectory can vary significantly from the mission course to seek a lower MSL altitude depending on the value of the TF/TA ratio. The ground track, once calculated, is given as aircraft locations along with bank and heading angles discretized at 1-sec intervals.

The vertical trajectory is based upon the calculated ground track. Using current speed, discrete variations in aircraft normal load factors, and aircraft climb/dive performance constraints, a vertical tree structure of possible trajectories is calculated (shown in the bottom part of fig. 2). Again, dynamic programming optimization is used to choose the optimal vertical trajectory with the least variation from terrain clearance altitude. The vertical trajectory positions as well as the climb and dive angles are then added to the ground track trajectory to provide a full three-dimensional (3-D) realizable trajectory. A complete description of this trajectory generation algorithm is available in the literature (refs. 7 and 11).

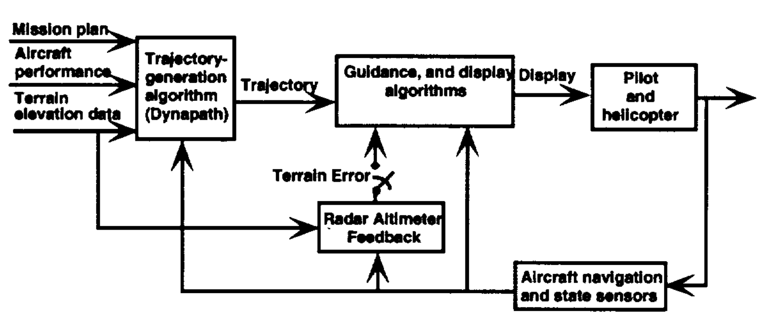

Figure 1. CALAHF system block diagram.

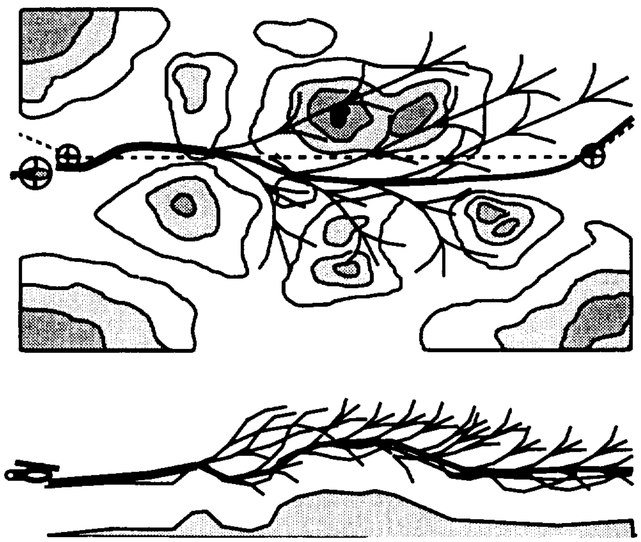

Figure 2. Trajectory tree generation.

2.2. Radar Altimeter Feedback

As described above, the trajectory generation algorithm is very much dependent upon the digital terrain data. An analysis was conducted using flight test data to ascertain the accuracy of the digital terrain data for the planned flight test area (ref. 12). The results of this analysis indicated that the minimum clearance altitude for flight should be 300 ft above ground level (AGL). This limitation was due to the inaccuracies in the digital terrain data and to obstacle avoidance considerations. During the analysis of this data it was observed that the inaccuracies primarily took the form of slowly varying deviations from the actual terrain. This observation led to the development of a real-time in-flight state estimator for the error between measured terrain altitude and terrain altitude derived from the digital terrain data (ref. 13).

The radar altimeter feedback algorithm is a Kalman filter that integrates radar altimeter, precision navigation and digital terrain data. The measurement of aircraft AGL altitude can, with these sources of data, be determined in two ways. The first is directly from the radar altimeter return. The second is to use the precision navigation data and search the digital terrain data for the predicted terrain altitude. Subtracting this predicated terrain altitude from the navigation system's current altitude gives the predicted AGL altitude. These two measurement methods are subject to different sources of error, both in frequency and content. The Kalman filter allows the modeling of the error sources and with both methods can produce an optimal estimate of the AGL altitude. The difference between this AGL altitude estimate and the predicted AGL altitude is fed back as terrain error. This terrain error is blended with the trajectory from the trajectory generation algorithm by linearly ramping the terrain error into each trajectory altitude over an 8-sec period. Since the radar altimeter feedback algorithm identifies the terrain elevation error, it allows significant reduction of the minimum terrain clearance altitude.

2.3. Guidance and Display Algorithms

The guidance and display algorithms combine current aircraft navigation and state information with the trajectory from the trajectory generation algorithm to provide a symbolic display to the pilot. The symbology is presented on a helmet-mounted display (HMD). Two formats of HMD symbology were used. The first format, shown in figure 3, presents the trajectory to the pilot by the use of an Earth-referenced pathway-in-the-sky. The pathway symbols give a 3-D perspective to 10 sec of the trajectory. The pathway is 100 ft wide at the bottom and 50 ft deep with vertical projections canted at 45 deg. The top center of each pathway symbol is the actual location of the desired trajectory. Precision guidance is given by a delta-wing phantom aircraft which leads at 3, 4, or 5 sec ahead of the current aircraft position along the desired trajectory. Also shown is the flightpath predictor symbol which predicts aircraft position using the same 3-, 4-, or 5-sec lead time. When this symbol is superimposed on the phantom aircraft, pursuit tracking of the phantom aircraft is achieved, allowing the pilot to precisely track the desired trajectory. Additional symbology is included that represents horizon and pitch reference lines (Earth-referenced) and the aircraft nose (body-referenced). The screen-referenced display symbols (those that do not move in relation to the pilot's head) include airspeed, heading tape, torque, radar altitude, and a slip indicator. Figure 4 shows the symbology in the decluttered format. The pathway symbology is reduced in size by 50% and is only shown ahead of the phantom aircraft. Figures 3 and 4 represent the same flight and trajectory situation with the symbology indicating a climbing right turn.

The pilot remains the final decision-maker on integrating desired trajectory information with current mission requirements, and the aircraft situation, conveying guidance to the pilot in this fashion, is referred to as pilot-centered. The pilot is provided with information about the guidance system's selected trajectory, the pilot's tracking accuracy, and the state of the helicopter. This information gives the pilot the flexibility to decide how closely to track the trajectory and the ability to override the trajectory decisions without loss of situational awareness. For example, the pilot can track the phantom aircraft with an intentional vertical and lateral bias similar to flying in formation. It also gives the pilot the ability to predict the

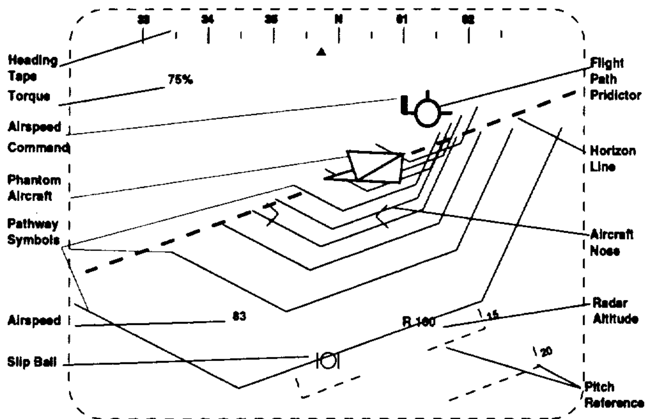

Figure 3. HMD symbology format.

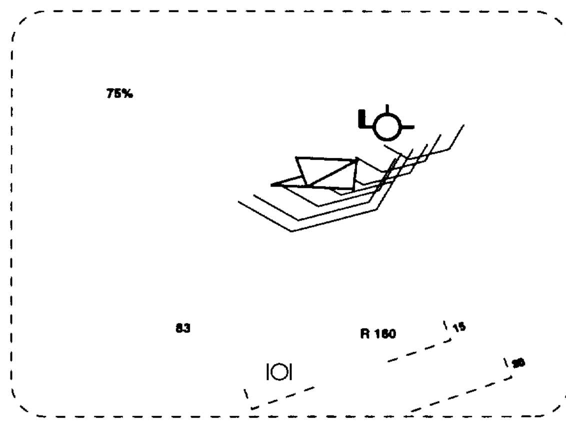

Figure 4. Decluttered display format.

phantom aircraft's maneuvers and to adjust the helicopter's position as the pilot desires.

The trajectory generation algorithm currently does not receive information on obstacles such as trees and towers. Consequently, the pilot is responsible for obstacle avoidance. The pilot uses the Earth-referenced trajectory symbols to determine conflicts with any obstacles he may visually detect along the desired trajectory. If a conflict is observed, the pilot can disregard the guidance to avoid the obstacle and then track back to the desired trajectory when it is safe. This gives the pilot the capability to use the trajectory guidance as precision guidance when no obstacles are detected and general navigation guidance when obstacles are encountered. This pilot-centered design is in contrast to traditional flight director designs in which the pilot is required to precisely follow pitch and bank steering bars to follow a predetermined course. Using a traditional flight director, the pilot is required to make corrections without full awareness of the aircraft's surroundings. With the CALAHF guidance system, the pilots can use their own judgment about how to use the guidance information while preserving their situational awareness of the surroundings.

3. Aircraft System Integration

The U.S. Army and NASA Ames Research Center have completed an extensive flight evaluation of the CALAHF system. The aircraft that is being used for the evaluation is the Army's NUH-60A STAR helicopter. The STAR is a Sikorsky Blackhawk helicopter that has been extensively modified to serve as a research aircraft for the U.S. Army (ref. 14). The primary modification was the installation of the Army Digital Avionics System (ADAS), which provides digital control and display of all cockpit functions through five multifunction displays (MFD). The ADAS manages the flight, engine, and navigation/communication display functions of the helicopter. It performs interactive control/display functions including including setting of switches and checklist accomplishment. In addition, when warnings or cautions occur, the ADAS presents the appropriate emergency procedure.

Figure 5 is a block diagram of the CALAHF system, as implemented in the STAR. The heart of the system is a general purpose Motorola 68030/68020-based multiprocessor Versa Module Eurocard (VME) computer running a real-time operating system. Connected to the VME on a 1553B network are a Collins RCVR-OH Global Positioning System (GPS) receiver, a Litton LN-39 Inertial Navigation Unit (INU), a Honeywell Integrated Helmet Mounted Display and Sighting System (IHADSS), three programmable Collins Control and Display Units (CDU), and an IBM PS2 computer. Also connected to the VME is a Silicon Graphics 4D/120 workstation, via a fiber optic SCRAMNet network, and an 386 AT personal computer, via a serial line. The VME is also connected to the ADAS system as a remote terminal on its 1553B network, allowing access to aircraft, navigation, and radar altimeter data.

The VME computer executes the trajectory generation and radar altimeter feedback algorithms, integrated navigation processing, mission plan storage and retrieval, network control, and overall system software. The VME provides the aircraft state, mission plan, digital terrain elevation data (DTED), and guidance algorithm control data to generate the trajectory output. The VME passes the trajectory and the current aircraft state information to the Silicon Graphics at a synchronous 20-Hz rate through the SCRAMNet interface for pilot display generation. Control of the CALAHF system is through the CDUs located both in the pilot's console and the engineer's

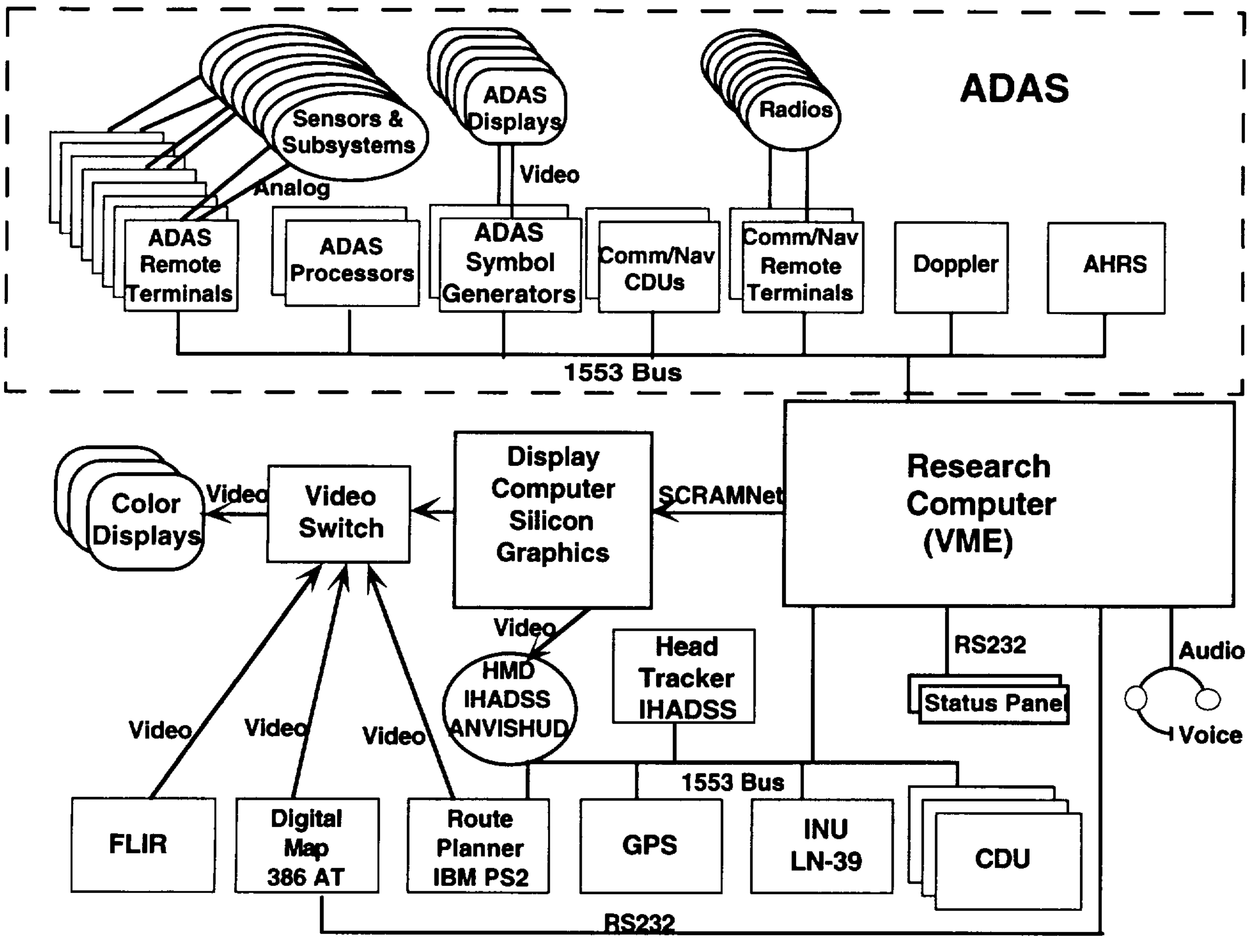

Figure 5. NUH-60A STAR systems diagram.

station. The CDUs allow mode control, selection of CALAHF flight and display parameters, and mission plan editing.

The navigation integration includes a military P-Code GPS to provide high-accuracy position data and an INU to provide high-rate aircraft state information. The navigation software filters and smooths the GPS and INU data, providing a continuous output for pilot display. The navigation software on the VME receives the aircraft state data from the GPS at 1 Hz and the INU at 32 Hz via the 1553B. The filters subtract the 1-Hz position information from the GPS and the corresponding INU information to determine latitude, longitude, and altitude corrections. The corrections are then ramped back into the INU at 8 Hz. Thus the navigation solution for the INU incorporates the accuracy of the P-Code GPS in near-continuous time (32 Hz).

The HMD system includes the IHADSS and the Silicon Graphics computer. The IHADSS provides the actual helmet display device and the head positioning sensor (fig 6). The Silicon Graphics workstation contains the software that generates the display symbology shown previously in figures 3 and 4, and provides display symbology to the IHADSS via an RS-170 video interface. This interface enabled the Army to quickly integrate a set of Aviator's Night Vision Imaging System goggles with the Elbit Head-Up Display (ANVIS/HUD) for their night evaluations of the CALAHF system.

A color digitized map of the flight test area is generated by the 386 AT PC and presented in the cockpit on a sunlight-readable color monitor manufactured by Smiths Industries. Superimposed on the map is the current mission plan, helicopter position, and desired trajectory. The map allows the pilot to maintain a global mission perspective. An automated mission planning and replanning capability is provided by the IBM PS2 computer.

The NUH-60A STAR helicopter has a self contained data recording capability. Aircraft state sensor, computed trajectory, and pilot tracking information are recorded on

Figure 6. Pilot in cockpit of the NUH-60A STAR.

a VME memory board with battery backup. This data is transferred to digital tape upon mission completion. Video information from the aircraft's nose-mounted FLIR 2000 forward-looking infrared imaging system (FLIR Systems) is combined with the HMD symbology and recorded along with aircraft communications on a videotape recorder.

4. Flight Evaluation

A three-phase flight evaluation of the CALAHF system integration was conducted on the STAR helicopter. The first phase, a functional evaluation, was executed during the summer and fall of 1992. The objective of this phase was to validate software and hardware systems integration (ref. 9). Phase 2, the engineering flight evaluation, was conducted between winter 1992 and spring 1993, and is discussed in detail below. The final phase was an operational evaluation conducted by the U.S. Army during the summer and fall of 1993. The primary purpose of the operational evaluation was to demonstrate the CALAHF system to active-duty military personnel and U.S. helicopter manufacturers. A limited night evaluation was also conducted using the ANVIS/HUD with the CALAHF symbology.

The engineering flight evaluations were conducted in a mountainous region just south of Carlisle, Pennsylvania. A DMA DTED Level I data base for the area, which covers 77°45' to 77°00' W by 39°45' to 40°15' N was obtained for the evaluation. The terrain is fairly rugged, with elevations ranging from 500 to 2100 ft. Shown in figure 7 is a contour map of the test area with a reference origin of 40°03'45" N by 77°18'45" W. Superimposed on the map is a series of navigation waypoints connected by dashed lines, which indicate the mission plan. The waypoints are labeled A through K. Because of time considerations for the flight evaluation, two mission plans were developed using these waypoints. The first, [NE–SW], started from the northeast at waypoint A and continued southwest to waypoint H. The second, [SW–NE], started from the southwest between K and G and continued northeast to A. As can be seen, both mission plans include essentially the same terrain.

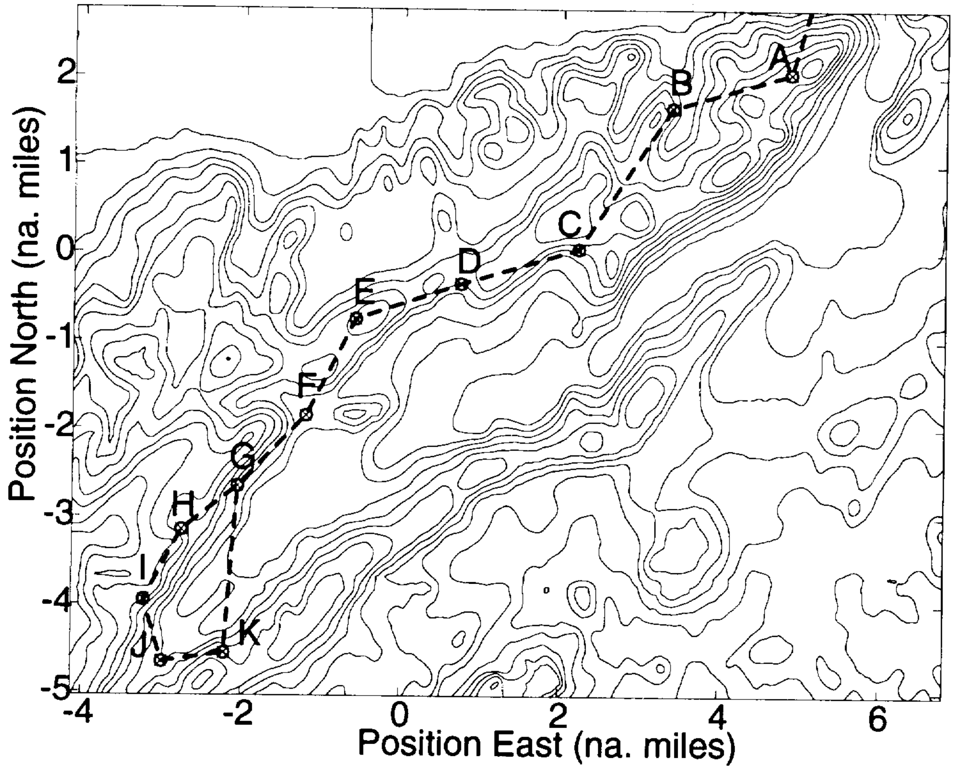

Figure 7. Flight evaluation area and mission waypoints.

Four pilots from the U.S. Army Communication Electronics Command (CECOM) and NASA Ames Research Center performed a flight evaluation of the system. Each pilot had participated earlier in the simulation activities of the CALAHF system (ref. 8). The Army pilots contributed vast helicopter tactical mission experience as well as aircraft-specific experience to the evaluation. Their operational experience was complemented by that of the NASA pilots, who have considerable research experience in the development and evaluation of advanced systems and concepts in conventional rotary-wing and one-of-a-kind aircraft. For the flight test, the evaluation pilot was in the left-hand seat and a safety pilot was in the right-hand seat of the aircraft. The evaluation pilot's sole function was to fly the aircraft using IHADSS and the CALAHF symbology. The safety pilot was responsible for overall aircraft control, communications, and any other necessary cockpit functions. The flight engineers were responsible for data collection and overall project control.

The two primary objectives of the flight evaluation were (1) to establish the suitability of the flightpath trajectory of the CALAHF system and (2) to evaluate the pilots ability to track the CALAHF symbology. Each of the four pilots flew the flight evaluation test matrix shown in table 1, and provided a wide array of tracking performance data. A total of 12 configurations were flown. The first configuration was flown using the NE–SW mission at 80 knots with a set clearance altitude of 300 ft. The trajectory generation algorithm used a maximum bank angle of 20° for trajectory control. The HMD symbology used a 4-sec lead time for the phantom aircraft, and 10 pathway symbols were displayed. The trajectory-generation algorithm was in the TF mode (i.e., precise following of the mission waypoints). In the second configuration, the TF/TA mode was evaluated over the SW–NE mission allowing the system to seek lower-altitude terrain. The terrain clearance altitude was lowered to 150 and 125 ft, respectively, in the third and fourth configuration by using the radar altimeter feedback algorithm. All subsequent configurations also used the radar altimeter feedback to allow evaluation at the tactically advantageous 150-ft terrain clearance altitude. Airspeed was varied in configurations 5 and 6. In configuration 7 the trajectory-generation algorithm's maximum bank angle was increased to 30°, allowing more aggressive maneuvers in seeking lower terrain. The phantom aircraft lead time was increased to 5 sec in configuration 8, then decreased to 3 sec in configuration 9. This lead time affects pilot tracking performance and workload in the pursuit tracking of the phantom aircraft with the flightpath predictor. The decluttered

Table 1. Engineering evaluation test matrix

Configuration	Mission plan	Airspeed, knots	Clearance altitude, ft	Maximum bank, deg	Lead time, sec	Pathway	TFTA ratio
1	NE–SW	80	300	20	4	10 lines	TF
2	SW–NE	80	300	20	4	10 lines	TFTA(.1)
3	NE–SW	80	150RA*	20	4	10 lines	TFTA(.1)
4	NE–SW	80	125RA*	20	4	10 lines	TFTA(.1)
5	SW–NE	110	150RA*	20	4	10 lines	TFTA(.1)
6	NE–SW	40	150RA*	20	4	10 lines	TFTA(.1)
7	NE–SW	80	150RA*	30	4	10 lines	TFTA(.1)
8	SW–NE	80	150RA*	20	5	10 lines	TFTA(.1)
9	NE–SW	80	150RA*	20	3	10 lines	TFTA(.1)
10	SW–NE	80	150RA*	20	4	Declutter	TFTA(.1)
11	SW–NE	80	150RA*	20	4	10 lines	TFTA(.05)
12	NE–SW	80	150RA*	20	4	10 lines	TF

RA* = radar altimeter feedback.

symbol set was used in configuration 10. The TF/TA ratio was reduced by 50% allowing greater deviations from the mission course with a lower-altitude trajectory in configuration 11. Finally, the TF mode was repeated in configuration 12, but with a 150-ft terrain clearance altitude.

The runs were initiated along the first leg of the mission course with the trajectory guidance information displayed on the HMD. The pilot was asked to track the phantom aircraft through the mission course while avoiding obstacles. At clearance altitudes below 300 ft, the pilot was required to occasionally override the trajectory guidance for obstacle avoidance. After each run the pilots were asked to comment on the ease or difficulty of flying that configuration. The NASA pilots were also required to rate the handling qualities of the aircraft and system while performing the task, using the Handling Qualities Rating (HQR) scale developed by Cooper and Harper (ref. 15). The HQR scale gives a numerical score between 1 and 10, with 1 being the best score and 10 being the worst, for the pilot workload required to achieve a desired level of performance. The desired level of performance for the task was to maintain the aircraft within 1 standard deviation of 50 ft vertically and 100 ft laterally of the desired trajectory. The pilot tracking performance was measured by comparing the trajectory generated by the CALAHF system with the actual trajectory flown by the pilots. To minimize the effect of pilot fatigue on performance, pilots flew only three to four consecutive runs per flight.

5. Results And Discussion

For all evaluation configurations, the pilots were able to maintain the desired level of performance using the CALAHF system. Representative examples of the ground tracks flown by the pilots using the system in the TF/TA mode for both the NE–SW and SW–NE missions are shown in figure 8. As can be seen, the TF/TA flights generally follow the mission course while maneuvering for lower terrain. A representative sample of the vertical trajectory flown by the pilots using the CALAHF system is shown in figure 9. The plot shown is that of a TF flight flown at a 150-ft clearance altitude (configuration 12). The aircraft altitude and commanded altitude are displayed as functions of distance traveled from waypoint A. As can be seen, the pilot is able to track the commanded altitude closely. Also displayed in the figure are plots of predicted terrain and measured terrain. The predicted terrain is that determined by the aircraft precision navigation system and the digital terrain data base. The measured terrain is calculated by subtracting the aircraft radar altimeter measurement from the mean sea level (MSL) altitude measured by the navigation system. The predicted terrain elevation generally matches

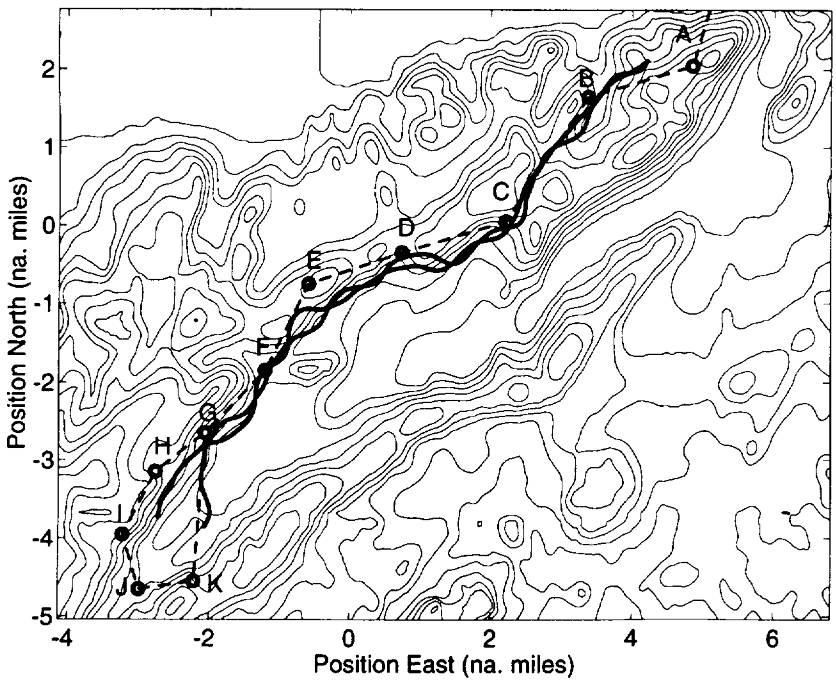

Figure 8. Example ground track.

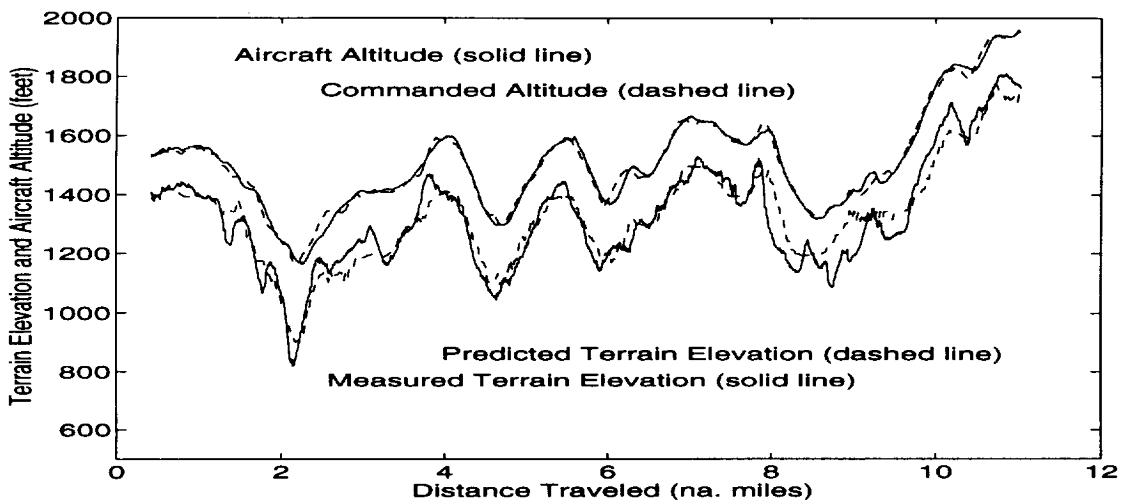

Figure 9. Example vertical profile.

terrain elevation generally matches the measured terrain elevation but, as discussed earlier, there are areas of slight disagreement. These discrepancies necessitated the use of the radar altimeter feedback algorithm to allow flights at the 125- and 150-foot terrain clearance altitudes.

Statistical performance results are shown in figure 10. The system dependent variables of MSL altitude, above ground level (AGL) altitude, and pilot tracking performance both vertically and laterally are shown. For each configuration the statistical mean for all flights is shown surrounded by the standard deviation. Table 2 shows the HQRs reported by the NASA research pilots. The HQRs for all configurations indicate that the CALAHF system required moderate to considerable pilot compensation. During periods of moderate to heavy turbulence, pilot compensation was reported to be extensive in most cases. These HQRs show an increase in pilot workload from the minimal to moderate levels achieved in simulation (ref. 8). This increase is attributed primarily to aircraft vibrations, natural lighting, and "real world" turbulence that were not modeled adequately during the simulation phase of the project (ref. 16).

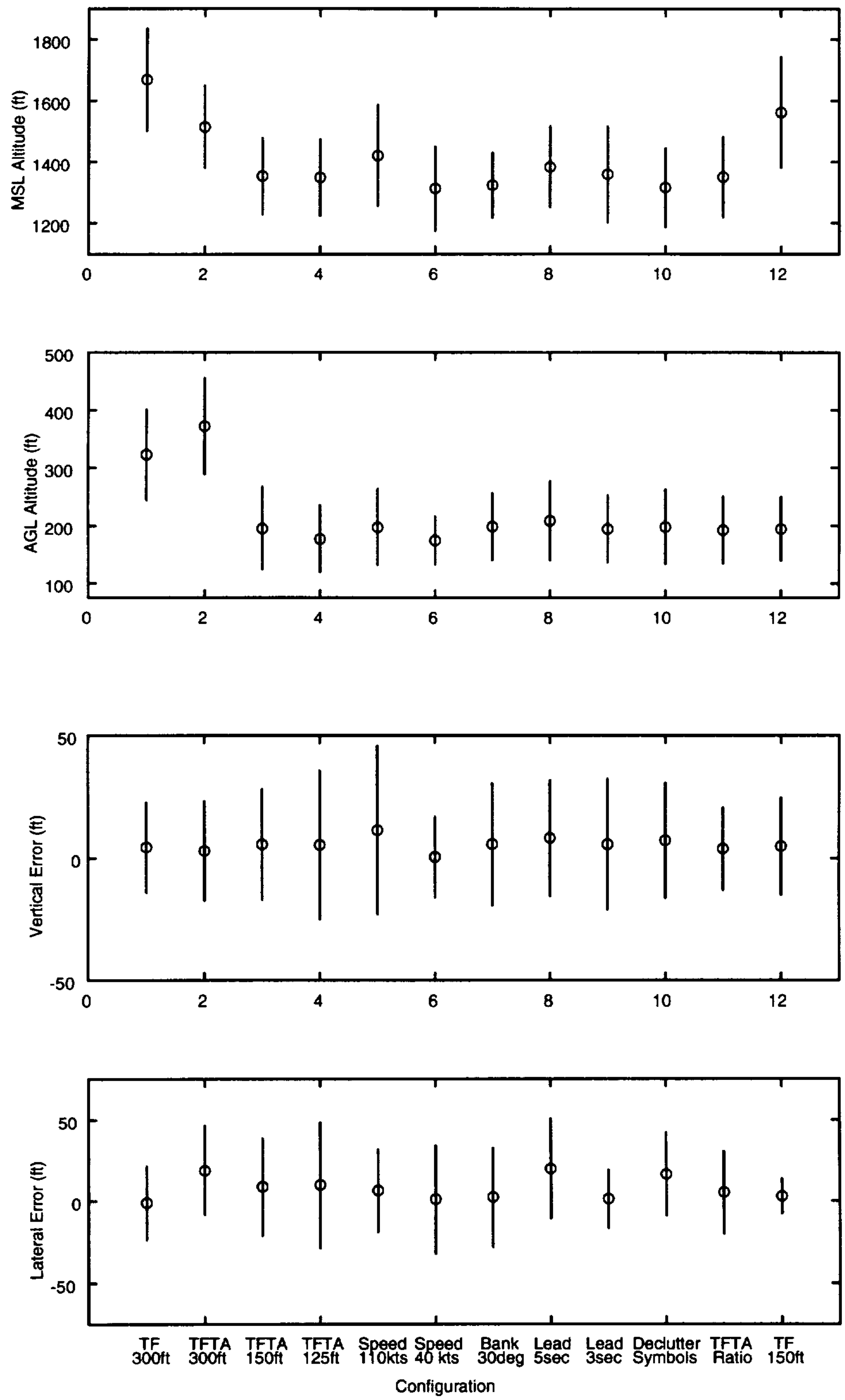

Figure 10. Statistical performance results.

Table 2. Pilot ratings

Configuration	1	2	3	4	5	6	7	8	9	10	11	12
Pilot 1	5	5	5	NF	5.5	NF	5	5	5.5	5	5	5
Pilot 2	3/4.5*	4/6*	4/6*	6*	4/6*	6*	6*	4.5/6*	5	6*	4	3

* = turbulent flight conditions.
NF = not flown.

As can be seen in figure 10, there is a ~150-ft average MSL altitude reduction during the mission when the TF/TA mode is used instead of the TF mode. This reduction is evident for configurations both with and without the radar altimeter feedback (configurations 2 and 3 and configurations 1 and 12). It is also interesting to note that the system flown in the TF/TA mode at the 300-ft terrain clearance altitude (configuration 2) has a lower overall MSL altitude than the TF mission flown at 150 ft aided by the radar altimeter (configuration 12). The radar altimeter feedback also reduces the spread in the AGL altitude, as can be seen by the 20% reduction in the standard deviations for configurations 1and 12 and 2 and 3. The pilot tracking performance is best for the TF configurations (1 and 12) and decreases slightly overall for the TF/TA configurations (2 through 11). In all cases the pilots were able to track the guidance system within 1 standard deviation of 50 feet vertically and laterally throughout the evaluation. The 125-ft clearance altitude configuration has a slightly lower MSL altitude than the 150-ft clearance altitude configuration. It was felt that 150 ft should be the lowest terrain clearance altitude flown for other areas with similar terrain and obstacles because of the number of obstacle-avoidance maneuvers required of the pilots, as indicated by the decrease in pilot tracking performance, and pilot comments. Increased airspeed (configuration 5) has the primary effect of slightly increasing the average MSL altitude over that with configuration 3. Conversely, the 40-knot configuration has a slightly lower MSL altitude. These airspeed effects are due to the effective climb-and-dive aircraft performance increase at lower speeds. It should be noted that while there is a decrease in MSL altitude, both Army pilots felt the system served no tactical advantage for flight at 40 knots 150 ft above the terrain. The increase in maximum bank angle to 30° also slightly lowers the MSL altitude but pilot workload increases, as indicated by the decrease in tracking performance. Increasing the phantom aircraft lead time does reduce the tracking performance but without a reduction in workload, as indicated by the HQRs being the same as for configuration 3. The reduction of the lead time does increase the pilot tracking performance, but with a corresponding increase in workload. The decluttered symbology format provides similar performance and workload results as the original symbology. Pilots reported that the declutter mode enabled them to more closely monitor the terrain for obstacles, but provided reduced turn information because of the smaller pathway symbols. The decluttered symbology set may be advantageous during poor visibility conditions or at night. Decreasing the TF/TA ratio produced a slight decrease in MSL altitude without any noticeable difference in pilot performance or workload.

From these test configuration results a reasonable system flight envelope can be recommended. The system should be operated in either the precise mission-following (TF) mode or in the terrain maneuvering mode (TF/TA) with the lower TF/TA ratio. The recommended speeds range from 80 to 110 knots. The terrain clearance altitudes for rugged terrain should not go below 150 ft when the system is aided by feedback from the radar altimeter or 300 ft when aiding is undesirable. Since both limits are based primarily upon the accuracy of the digital terrain database and the expected obstacle height, these clearance altitudes may be different in other areas. With more accurate data or an obstacle-detection sensor clearance altitude limits may be reduced. A piloted simulation of the system integrated with an obstacle-detection sensor has been conducted for terrain clearance altitudes of 25 ft (ref. 17). The CALAHF system also has significant utility in areas that do not have much variation in terrain altitude, or over water when a near-terrain precision guidance and navigation capability is required. The set clearance altitude should then be limited to expected obstacle height. Both symbology sets give the capability to precisely follow an arbitrary multiwaypoint mission. The full pathway symbology is more useful when precise trajectory control is required, such as during an approach to a landing zone. The decluttered symbology format may be more useful during reconnaissance operations in which the pilot is willing to sacrifice some precision for reduced display clutter. The recommended phantom lead time should be 4 sec. The lead time required is somewhat dependent on aircraft response characteristics and may need to be adjusted for other aircraft or helicopter types.

6. Conclusions

A near-terrain, covert-maneuvering guidance system that automates the processing of precision navigation information, mission requirements, and terrain flight control has been developed and extensively flight evaluated. The pilots were able to successfully track the helmet-mounted display symbology with precision while maintaining a high degree of situational awareness. The system can be flown safely at terrain clearance altitudes of 300 ft, or down to 125 ft when aided by radar altimeter feedback, in mountainous regions similar to the one used during this evaluation. The system is currently limited by the pilot's ability to visually detect and avoid obstacles. Additional research is being conducted by NASA and the Army to integrate an obstacle-avoidance sensor with the CALAHF system for lower terrain clearance altitudes.

7. References

1. Sridhar, B.; Cheng, V. L.; and Swenson, H. N.: Status of Automatic Guidance Systems for Rotorcraft in Low Altitude Flight. AGARD CP-504, Oct. 1991.
2. Clifford, J. E.: PAVE Low III A Long Awaited Capability, Lessons Learned and Projections. IEEE National Aerospace and Electronics Conference (NAECON), Dayton, Ohio, May 1979.
3. Smith, C.: Systems Commonality: Integrated Avionics for the MH-47E and the MH-60K. IEEE/AIAA 10th Digital Avionics Systems Conference (DASC), Los Angeles, Calif., Oct. 1991.
4. Russ, D. E.; Houtz, J. E.; and Rauthstein, S. E.: Evaluations of Alternate TF/TA System Designs Using Pilot in the Loop Simulations. AGARD CP-387, Oct. 1985.
5. Dorr, D. W.: Rotary Wing Aircraft Terrain Following/Terrain Avoidance Concepts. AIAA Guidance, Navigation and Control Conference, Aug. 1986.
6. Swenson, H. N.; Hardy, G. H.; and Morris, P. M.: Simulation Evaluation of Helicopter Terrain Following/Terrain Avoidance Concepts. AIAA/IEEE 8th DASC, San Jose, Calif., Oct. 1988.
7. Swenson, H. N.: Computer Aiding for Low-Altitude Helicopter Flight. NASA TM-103861, May 1991.
8. Swenson, H. N.; Zelenka, R. E.; Hardy, G. H.; and Dearing, M. G.: Simulation Evaluation of a Low-Altitude Helicopter Flight Guidance System Adapted for a Helmet-Mounted Display. NASA TM-103883, Feb. 1992.
9. Swenson, H. N.; Jones, R. D.; and Clark, R.: Flight Evaluation of a Computer Aided Low-Altitude Helicopter Flight Guidance System. NASA TM-103998, Jan. 1993.
10. Babiak, N.: The Defense Mapping Agency and Tomorrow's Advanced Aerospace Warfare Systems. IEEE NACON, Dayton, Ohio, 1990.
11. Peckelsma, N. J.; and Denton, R. V.: Optimal Guidance with Obstacle Avoidance for Nap-of-the-Earth Flight. NASA CR-177515, Dec. 1988.
12. Zelenka, R. E.; and Swenson, H. N.: Appraisal of Digital Terrain Elevation Data for Low-Altitude Flight. NASA TM-103896, Jan. 1992.
13. Zelenka, R. E.; Zee, Y.; and Zirkler, A.: Flight Test Development and Evaluation of a Kalman Filter State Estimator for Low-Altitude Flight. IEEE Conference on Control Applications, Vancouver, Canada, Sept. 1993.
14. Operator's Manual NUH-60A Helicopter, U.S. Army Avionics Research and Development Activities, TM-55-1520-237(ADAS)-10, Fort Monmouth, N.J., Jan. 1987.
15. Cooper, G. E.; and Harper, R. P.: The Use of Pilot Ratings in the Evaluation of Aircraft Handling Qualities. NASA TN D-5113, 1969.
16. Dearing, M. G.; Swenson, H. N.; Hardy, G. H.. Zelenka, R. E.: Computer Aiding for Low-Altitude Flight, Simulation to Flight: A Case Study. SAE #932518, AeroTech '93, Costa Mesa, Calif., Sept. 1993.
17. Zelenka, R. E.; Swenson, H. S.; Dearing, M. G.; and Hardy, G. H: Simulation Development of a Forward Sensor-Enhanced Low-Altitude Guidance System. 12th IEEE/AIAA DASC, Fort Worth, Tex., Oct. 1993.

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
August 1994

3. REPORT TYPE AND DATES COVERED
Technical Memorandum

4. TITLE AND SUBTITLE
Design and Flight Evaluation of an Integrated Navigation and Near-Terrain Helicopter Guidance System for Nighttime and Adverse Weather Operations

5. FUNDING NUMBERS
505-64-36

6. AUTHOR(S)
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Ames Research Center
Moffett Field, CA 94035-1000

8. PERFORMING ORGANIZATION REPORT NUMBER
A-94112

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA TM-108837

11. SUPPLEMENTARY NOTES
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12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified — Unlimited
Subject Category 04

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

NASA and the U.S. Army have designed, developed, and flight evaluated a Computer Aiding for Low-Altitude Helicopter Flight (CALAHF) guidance system. This system provides guidance to the pilot for near-terrain covert helicopter operations. It automates the processing of precision navigation information, helicopter mission requirements, and terrain flight guidance. The automation is presented to the pilot through symbology on a helmet-mounted display. The symbology is a "pilot-centered" design which preserves pilot flexibility and authority over the CALAHF system's automation. An extensive flight evaluation of the system has been conducted using the U.S. Army's NUH-60 STAR (Systems Testbed for Avionics Research) research helicopter. The evaluations were flown over a multiwaypoint helicopter mission in rugged mountainous terrain, at terrain clearance altitudes from 300 to 125 ft and airspeeds from 40 to 110 knots. The results of these evaluations showed that the pilots could precisely follow the automation symbology while maintaining a high degree of situational awareness.

14. SUBJECT TERMS
Helmet-mounted display, Helicopter flight test, Near-terrain navigation and guidance

15. NUMBER OF PAGES
16

16. PRICE CODE
A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified		