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Development and Flight Test of Terrain-Referenced Guidance with Ladar Forward Sensor

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Military aircraft regularly conduct missions that include low-altitude, near-terrain flight to increase covertness and payload effectiveness. Civilian aircraft operate in this regime during airborne fire fighting, police surveillance, search and rescue, and helicopter emergency medical service applications. Several fixed-wing aircraft now employ terrain elevation maps and forward-pointed radars to achieve automated terrain following or terrain avoidance flight. Similar systems specialized to helicopters and their flight regime have not received as much attention. A helicopter guidance system relying on digitized terrain elevation maps has been developed that employs airborne navigation, mission requirements, aircraft performance limits, and radar altimeter returns to generate a valley-seeking, low-altitude trajectory between waypoints. The guidance trajectory is symbolically presented to the pilot on a helmet-mounted display. In this work, a wide field of view laser radar forward sensor has been incorporated into this guidance system to expand the system's operational flight envelope and to assist the pilot in obstacle detection and avoidance. The development and flight test results of this guidance system are presented. Missions to 75 ft altitude at 80 kn in the presence of unmapped natural and man-made obstacles were achieved while the pilot maintained situational awareness and tracking of the guidance trajectory.

I. Introduction

THE risk and crew workload inherent in flight operations near the ground or in poor weather are severe, with navigation, guidance, and obstacle avoidance demanding high attention. Flights are commonly canceled because of weather or pilot and aircraft limitations that restrict flights to above local terrain maximums. For the military, operations at close proximity to the terrain are necessary to increase covertness while penetrating enemy territory and to increase survivability and payload effectiveness. Civilian airborne fire fighting, police surveillance, search and rescue, and helicopter emergency medical service also involve flight in this regime as an essential element of their flight profile.

Advances in computational capacity, sensor capability, and signal processing have produced a variety of avionic aids for this flight regime. Much of the emphasis has focused on the ability to detect and avoid obstacles and terrain with passive sensors, such as forward-looking infrared and low-level light television, and with active sensors like radar. Levels of automation for low-altitude flight range from head-down moving map displays of terrain avoidance (TA) clearance planes to full authority autopilot terrain following (TF) systems. TA radars provide a top-down view of terrain above a given clearance plane, which the pilot can use to execute safe lateral avoidance maneuvers. TF radars allow automatic contour (constant above ground level) flight by sending control commands to the aircraft for safe climb/dive over terrain or obstacles in the flight path. The pilot is also given a display for TF monitoring or for manual operation. Such decoupled lateral TA or vertical TF maneuvering systems are operational in aircraft such as the A-7, F-111, and B-1 (Refs. 1 and 2). In many of these systems, the pilot is obligated to perform functions such as navigation and guidance while monitoring the TF or TA system. The integration of these functions in a synergistic manner is a difficult challenge, primarily because of their mission, aircraft, and sensor specific nature.

A technology development program at NASA Ames Research Center in helicopter flight automation[3] has included the development of a low-altitude, TF/TA guidance system for helicopters.[4] The system employs terrain elevation maps in calculating its guidance trajectories. Earlier stored map-based systems, developed by the U.S. Air Force, among others, demonstrated this capability for aircraft and missile applications.[5] By applying a cost function over an intended route between waypoints, a three-dimensional TF/TA route may be calculated in real time. The minimization of radiated energy from the aircraft is of concern during military operations where covertness is crucial and is a prime motivation for using stored digitized terrain elevation maps for navigation or guidance.

After evaluation in several piloted simulations, this TF/TA guidance system was implemented for flight evaluation with the U.S. Army Command/Control and Systems Integration Directorate, Ft. Monmouth, NJ, aboard their NUH-60 Systems Testbed for Avionics Research (STAR) helicopter. To improve above-ground-level aircraft positioning, a Kalman filter (KF) was developed that blends radar altimeter measurements, navigation system vertical position, and stored digital terrain data. When augmented with this radar altimeter filter, operations to 150 ft above ground level (AGL) altitude in good visibility at 80 kn were achieved in flight test.[6]

To allow flight at even lower altitudes, a forward-looking sensor must be incorporated to locate unmapped obstacles and provide a near-field, look-ahead capability. In this work, a wide field of view laser radar (or ladar) sensor was integrated into the guidance system. The sensor's returns were used to generate an inertially referenced,

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aircraft-centered obstacle database. The trajectory was then altered to avoid terrain and obstacles along its path, allowing for reduced altitude operation and adding an obstacle avoidance (OA) capability to the guidance system.

The paper begins with a description of the low-altitude helicopter guidance system as it evolved in three phases: 1) the baseline terrain map-based system, 2) the radar altimeter augmented system, and 3) the forward sensor equipped system. The phases built upon one another and progressively increased in complexity and capability. The flight integration of the forward sensor enhanced system is then detailed, followed by flight test results.

II. Guidance System Description

The low-altitude helicopter guidance system will be described through its three phases of development, each developed in motion-based, piloted simulation and then evaluated and improved through flight test. Figure 1 is a combined block diagram of the guidance system through its development phases.

A. Baseline (TF/TA) Guidance System

The baseline guidance system computes in real time a valley-seeking TF/TA trajectory based on mission requirements, aircraft performance capabilities, airborne navigation, and digitized terrain elevation data (Fig. 1). The system's trajectory generation algorithm maintains a cost function that seeks to minimize mean sea level (MSL) altitude, heading change from a straight line nominal path between waypoints, and lateral offset from the nominal path. The cost function is applied to candidate trajectories from the current aircraft position over discrete pitch and roll angles. The lowest cost function trajectory (for the next 30 s) is then selected.[4] Adjusting constants of the cost function allows varying degrees of weighting to be applied to each performance criterion. The pilot selects aircraft performance limits and constants for the system. These include maximum bank, climb, and dive angles, normal load factor, and desired velocity and set clearance altitude. Set clearance altitude is that AGL altitude to which the guidance algorithm will nominally seek. By severely penalizing, for example, those trajectories that deviate from the straight line nominal course (in heading and position), a straight line contour trajectory is generated. Such flight exclusively in the vertical plane is termed TF flight. Decreasing the penalty on these same two parameters allows lateral movement and yields a meandering TF/TA flight profile. A general flight plan, consisting of a series of course waypoints, is supplied by a mission planner, or simply input by the crew, and can be changed in flight. The mission planner, if supplied with ground-based threat information, will choose course waypoints sensitive to these hazards.

The trajectory generated by the guidance system is presented symbolically to the pilot through a helmet-mounted display (HMD), the Integrated Helmet and Display Sighting System (IHADSS). The Honeywell IHADSS is standard equipment for the U.S. Army's AH-64 Apache helicopter. In our use of this HMD, guidance trajectory

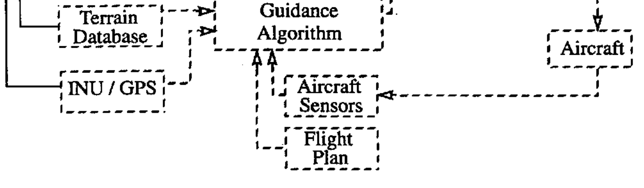

Fig. 1 Guidance system block diagram: ----, baseline (TF/TA) guidance system; ——, KF augmented (TF/TA) guidance system; and ▬, forward sensor augmented (TF/TA/OA) guidance system.

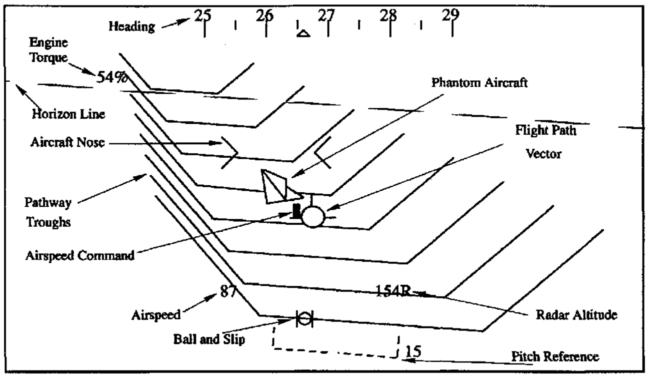

Fig. 2 Guidance system symbology.

alone is presented to the pilot; i.e., no overlapped imagery is employed. A pictorial of the pilot presentation symbology on the head-tracked HMD is shown as Fig. 2, which presents a climbing left turn trajectory. The pathway troughs and phantom aircraft are drawn in inertial space along the desired trajectory. The troughs are 100 ft wide at the base, 50 ft tall, and 200 ft wide at the top and are drawn in 1-s increments of the trajectory out to 8 s, based on the aircraft's airspeed. The top center of each pathway is the desired, computed trajectory. The phantom aircraft flies at the top center of the fourth trough (the desired trajectory 4 s in the future). The aircraft's flight path vector is also drawn on the HMD, as predicted 4 s ahead. Hence, by tracking the phantom aircraft with the flight-path vector, the pilot attempts to fly the desired TF/TA guidance trajectory. Additional aircraft status information also displayed includes magnetic heading, engine torque, airspeed, radar altimeter, and ball and slip indicator. A horizon line, pitch ladder, and aircraft nose chevrons are also given to improve situational awareness. An airspeed flight director tape reflects deviation from the pilot-selected, desired airspeed. Any of these symbols may be turned off by the pilot, allowing him to fine tune the display per his preferences and the conditions of the mission. This symbology set was developed over several piloted, motion-based simulations with a diverse group of pilots and gives desired trajectory tracking performance with minimal pilot compensation.[4]

Although the guidance trajectory is derived from a terrain elevation map, the AGL positioning of the aircraft is found from the difference between airborne navigation MSL altitude and the predicted terrain map elevation below the aircraft. The accessed value for terrain elevation is an imperfect approximation of the terrain and is referenced using the imperfect latitude-longitude output from the navigation system. A level 1 Defense Mapping Agency (DMA) digital terrain elevation data database consists of a uniform matrix of MSL terrain elevation values. Unrecorded features and map horizontal shifts have been observed in flight tests.[6] Because the terrain elevation stored in the DMA database is accessed via the latitude-longitude value of the navigation system, horizontal positioning errors will reference offset terrain data. The sum of these DMA errors, combined with those of the navigation system, can lead to large errors in the predicted absolute AGL altitude.

The baseline system's performance is principally limited in its ability to position itself above the terrain and its inability to detect and avoid unmapped obstacles, such as trees and wires. The above ground positioning limitation was found dominant and restricted flight to above 300 ft AGL at the operational design speeds between 80 and 130 kn. Nominal guidance trajectory settings included max climb/dive angles of $-6 \le \gamma_{\max} \le 6$ deg, vertical load of ±0.25 g from nominal, and bank angle of $20 < \phi_{\max} < 20$ deg. This baseline system was flight tested in day and night Visual Flight Rules (VFR) conditions.

B. Radar Altimeter Augmented (TF/TA) Guidance System

As discussed, combined vertical navigation and terrain database errors in the proposed flight test area established a minimum AGL altitude ceiling of 300 ft. Such flight altitudes greatly limited the benefit and effectiveness of the TF/TA guidance system, particularly to the military helicopter community, where operations restricted to such midlevel altitudes would not justify its cost and complexity.

The thin, solid blocks of Fig. 1 detail the extension to the baseline TF/TA guidance system resulting from a KF augmentation. The predicted AGL altitude, calculated as the difference in the navigation system MSL altitude and the stored map terrain elevation, together with the radar altimeter measurement, are blended in a KF to yield an estimate for the difference error from the predicted AGL altitude.[7] This difference error value, $\hat{h}_{err}$, is then used to alter the terrain elevation database referenced guidance trajectory at the AGL error blending block of Fig. 1. To ensure a smooth symbology presentation of the guidance trajectory to the pilot, the change in the value of $\hat{h}_{err}$ is ramped in linearly over the eight troughs presented. That is, (after initialization) the eighth trough is altered in vertical position by the full change in $\hat{h}_{err}$, but the first trough is only moved by $\frac{1}{8}$ of this $\Delta\hat{h}_{err}$. Such ramping does introduce a lag in the trajectory symbology, although the scheme is bounded at the eighth trough by the current value of $\hat{h}_{err}$. The solely airborne navigation and stored terrain elevation database referenced trajectory of the baseline system ($[\rho_{traj}]$) is modified with respect to the value of $\hat{h}_{err}$ to produce $[\rho'_{traj}]$. This modified trajectory is then presented to the pilot using the existing display laws and symbology.

The KF processing of the radar altimeter measurement was found robust and accurate in modifying the vertical position of the baseline terrain-referenced guidance system trajectories. The enhancement produced trajectories more reflective of the topography and allowed for lower altitude operation than that of the baseline guidance system. The minimum flight altitude was reduced from 300 ft AGL altitude to 150 ft at operational speeds from 80 to 130 kn (Ref. 6). Flight restrictions for the terrain-referenced guidance system were now governed by pilot obstacle detection and avoidance, which could be assisted by a forward-looking sensor.

C. Forward Sensor Augmented (TF/TA/OA) System

The forward sensor enhancement to the NASA/Army guidance system involved the addition of three distinct components: 1) a wide field of view forward-looking laser radar, 2) a terrain/obstacle database generated from sensor returns, and 3) a path manager, which modified the guidance trajectory if necessary after querying the sensor database (Fig. 1).

1. Forward Sensor

The forward sensor integrated was the Northrop Obstacle Avoidance System (OASYS) prototype sensor developed by the U.S. Army Night Vision Electronic Sensors Directorate, Ft. Belvoir, VA. The OASYS uses a laser radar to locate obstacles in a 25 deg by 50 deg field of view (FOV). The sensor attempts to detect all obstacles in this FOV, particularly wires. Extensive details of the design, development, and stand-alone flight evaluation of the OASYS can be found in Ref. 8 and will only briefly be described here.

Figure 3 presents a functional schematic of the laser radar, or ladar, sensor. The monostatic transmitter/receiver employs an 850-nm gallium aluminum arsenide diode and avalanche photodiode detector. The laser optics output a collimated circularly polarized beam to a holographic optical element (HOE). The HOE diffracts this beam from nominal to 15 deg and rotates to yield a scanning beam of 25 deg. By scanning the sensor in azimuth by 25 deg, a 25 × 50-deg field of view is achieved. The complete field of view is covered in 0.75 s. The sensor is designed to be eye safe at the 6.0-in. aperture and has a maximum range of 1968.5 ft (Ref. 8).

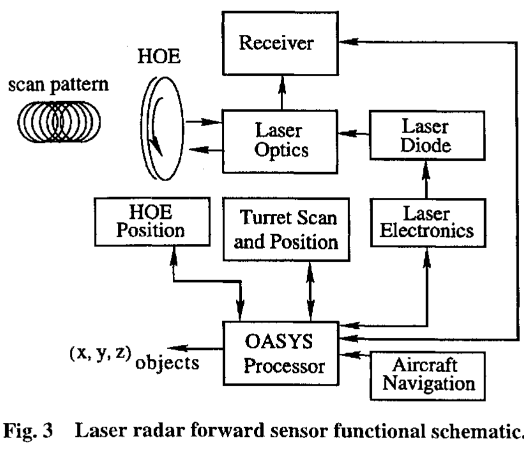

Fig. 3 Laser radar forward sensor functional schematic.

The range of any active sensor, including the OASYS ladar, is a function of many parameters. Target characteristics, atmospheric conditions, and wave incidence angle all greatly impact detection and range performance. The OASYS was designed to detect a 1-in.-diam wet wire at a 60-deg incidence angle at 400 m (1312.3 ft) in 2-km (6561.7 ft) visibility while flying at night. Range accuracy is 2.5 m (8.2 ft), with angular accuracy driven by boresighting error, estimated at 1 deg in azimuth and elevation. Performance of all laser wavelength sensors are quite limited in fog and rain. The OASYS program emphasized nighttime operations, and hence the OASYS sensor system was optimized for the night environment. Daytime performance is expected to be slightly degraded.[8]

For use in the NASA/Army TF/TA guidance system, only the OASYS sensor's valid detection returns are required. These returns, in either sensor or aircraft body coordinates, are necessary to construct a local, high-resolution database that includes the obstacles and terrain identified by the OASYS ladar. By considering the digital map-based TF/TA guidance trajectory with respect to this OASYS-determined database, modifications can be made to the trajectory that provide a lower altitude and an obstacle avoidance capability to the TF/TA guidance trajectory.

2. Sensor Generated Database

The terrain and obstacles located by the forward sensor are stored in an inertially referenced grid system with grid resolution of 10 m (32.8 ft). The area considered by the guidance system is 1500 m (4921 ft) square and is periodically shifted through the grid system such that its center position remains approximately below the aircraft. The database is updated with a group of OASYS detected objects, nominally at 10 Hz. The number of objects in each group varies with the scene content, aircraft orientation, and environmental conditions. In this context, objects include any detected obstacles, both man made (e.g., wires and buildings) and natural (e.g., ground itself and trees). The OASYS objects are received in aircraft body referenced coordinates and are immediately transformed into (world) inertial coordinates.

The quantized (32.8-ft) grid of the database to which each detected OASYS sensor object belongs is then determined. Several approaches to the blending of multiple returns to the same grid cell were considered. The fundamental tradeoff is to develop a processing scheme that will perform adequate noise rejection while maintaining elevation sensitivity in each grid. This is especially difficult and important for storing obstacles where two distinct elevation values exist at the same inertial location, e.g., an overhanging wire and the ground below it. Because of the limited number of forward sensor returns (and occasional lack of returns) for filling the sensor database, however, the approach was to address false sensor generated database effects during the subsequent (path manager) blending.

3. Path Manager

The path manager is used to alter the guidance trajectory in the event of an altitude clearance problem, as determined by the elevations of obstacles and terrain stored in the sensor generated database. A rectangle of variable width, extended from the previous trajectory trough to the next, is located in the sensor database. Its width was nominally set to 200 ft, which corresponds to the width of the top of the trajectory troughs (Fig. 2). Note that for an aircraft flying at 100 kn the 1-s spaced trajectory troughs translate to a separation of 169 ft. The highest elevation of the sensor database grids covered for each trough comparison rectangle is determined and used in accessing potential clearance problems with respect to the radar altimeter KF improved guidance trajectory. If no sensor returns are present, the DMA terrain map elevation is used. All adjustments made to the trajectory are in vertical position only, i.e., no lateral modifications are made. Note that the optimization about the cost function described earlier for the guidance trajectory is not recomputed; i.e., this is not a closed loop forward sensor trajectory solution.

To address the occasional errant sensor return and present a smooth guidance trajectory, several sequential steps are taken to adjust the guidance trajectory vertically. First, the maximum elevation from each consecutive group of four trough comparison rectangles is found. The trajectory is then connected vertically to these maximum elevations plus the pilot-selected obstacle clearance value. These new trough elevations are compared with those resulting from the radar altimeter KF augmentation, and the highest elevation of these two values is assigned for that particular trough. (Recall that the KF enhancement is based on airborne navigation, digital terrain data, and the downward-pointed radar altimeter and has virtually no look-ahead ability.) A final smoothing of the trajectory based on maximum climb and dive γ is then performed. Should the obstacle be so high that even progressively altering every trough does not clear the obstacle, the γ_{max} constraint is removed and all troughs are moved to that (constant) value of γ that will clear the obstacle at the desired setting. The pathway manager's modified guidance trajectory is depicted as $[\rho''_{traj}]$ in Fig. 1.

In this manner, the path manager's trough comparison rectangle values, found by querying the sensor database, are used to alter the trajectory if required. It is a conservative approach in that maximum elevation values assigned to the obstacle database are used and vertical modifications to the pathway are biased toward increasing trajectory elevation placement to ensure that all possible height hazards along the guidance trajectory are addressed. Resulting obstacle sensitive trajectories will yield AGL altitudes between the set clearance altitude and the set clearance plus obstacle clearance values. In rugged terrain areas, where stored terrain map elevations are particularly unreliable, the trajectories will be continuously adjusted because of sensor located hazards, and the AGL altitude will be closer to that of the sum of the selected set clearance and obstacle clearance values.

This approach for integrating a forward obstacle avoidance sensor into the terrain referenced guidance system has the advantage of using the existing flight proven components of the guidance system and was initially developed through motion-based, piloted flight simulation.[9] The repositioning of the trajectory only vertically also allows a thorough understanding of sensor characteristics and sensor database construction techniques to be understood through flight test before possibly more sophisticated (i.e., lateral with vertical repositioning) techniques being attempted.

III. Aircraft Integration

The low-altitude forward sensor augmented (TF/TA/OA) system was implemented and flight tested aboard a modified Sikorsky UH-60A Black Hawk helicopter. The STAR aircraft is operated by the U.S. Army Command/Control and Systems Integration Directorate, Ft. Monmouth, New Jersey. The laser radar sensor was mounted on the nose of the helicopter, whereas a forward-looking infrared (FLIR) camera was contained in a chin turret (Fig. 4). A color television camera was rigidly mounted inside the cockpit between the pilots. The television and FLIR are used only for engineering monitoring and are not presented to the pilot through his display or instrument panel. The components of the NUH-60A STAR are cataloged in Table 1.

Fig. 4 NUH-60A STAR test helicopter with OASYS ladar sensor.

Table 1 Test aircraft components

Component	Manufacturer model
Aircraft	U.S. Army Sikorsky UH-60A Black Hawk Helicopter
Flight computers	(2) Motorola 68030, (7) 68020 VME
	Silicon Graphics V35 Elan-V
	IBM PS/2
Pilot display	Honeywell IHADSS Helmet-Mounted Display
Navigation	Litton LN-39 INU
	Rockwell-Collins RCVR-OH GPS Receiver
Radar altimeter	Honeywell APN-209
Terrain database	DMA Level I Digital Terrain Elevation Data
Forward sensor	Northrop OASYS Laser Radar Forward Sensor

The NUH-60A STAR hosts the Army Digital Avionics System (ADAS). This system allows fully integrated control and display capabilities for the pilot and copilot through two identical pairs of multifunction displays. These displays provide digital monitoring of aircraft state and instrumentation and associated control. A flight engineer station at the rear of the aircraft includes an additional ADAS display for flight test direction and control. All components of this network are connected through a 1553B interface.

The principal flight computer for the guidance system is a Motorola 68030 and 68020 multiprocessor VERSAmodule Eurocard (VME) computer. The 68030 processor provides VME bus arbitration and the engineer station interface, whereas seven 68020 processors host the research application software in a real-time, multiprocessor environment. The TF/TA guidance algorithm is dedicated to one of the processors, with input/output distributed across the others. The VME computer acts as the central processor for the research work conducted on the aircraft and is interfaced to several other computers and devices. A 1553B interface connects the VME to the inertial navigation unit (INU) (32 Hz), global positioning system (GPS) (1 Hz), IHADSS (32 Hz), radar altimeter (8 Hz), and IBM PS/2 (8 Hz), the latter used as a route planner.

Navigation is provided by an integrated two-channel Precision-code GPS receiver and platform stabilized INU. The fan-type 4.3-GHz radar altimeter returned height above ground or closest terrain obstacle to altitudes of 1500 ft and through pitch and roll angles of 45 deg. Radar altimeter accuracy is specified to be 3 ft ±3% of actual altitude.

The terrain elevation database was Level I DMA DTED in 1 × 1° cells from 77 to 78° W longitude and from 39 to 41° N latitude. The database prediction of terrain elevation is found by forming a triangular plane of the nearest three posts of DMA data. The interpolated value of this plane below the aircraft is taken as the database elevation prediction.

Flight data were recorded at 5 Hz and included the guidance trajectory location and aircraft state information. Infrared or television video were also recorded for engineering use only.

IV. Flight Test Results

The flight test evaluation of the forward sensor augmented (TF/TA/OA) system and the earlier guidance system phases were conducted in flat terrain near Lakehurst, New Jersey, and in moderately rough terrain near Carlisle, Pennsylvania, just south of Harrisburg, Pennsylvania. The Lakehurst area was used primarily for system checkout and for flights over high-voltage wires. All flights were conducted in daylight, VFR conditions. The Carlisle area includes diverse features, such as flat plain sections and South Mountain, running diagonally northeast- southwest through the test area. The more rugged sections of the region contain rather densely populated deciduous trees. Most of the flight testing was conducted in the Carlisle area, whose terrain was most appropriate for evaluating a low-altitude TF/TA guidance system. The area, however, is not obstacle rich, in terms of manmade obstacles such as wires, towers, and structures. As a result, most of the Carlisle testing was focused on decreasing flight altitudes (compared with the earlier phases of the guidance system) amongst natural obstacles (trees, hills, and ridges). Such natural obstacles were still formidable and challenged the forward sensor equipped guidance system. Flight data discussed and presented in this report were collected during June/July 1994 and December 1994/January 1995. All flights were conducted during daylight with clear visibility conditions.

The evaluation of the TF/TA/OA guidance system included assorted combinations of speed, set clearance altitude, TF or TF/TA mission profile, obstacle clearance altitude, obstacle database construction algorithms, and forward sensor blending techniques over a test course of several waypoints. Mission speeds ranged from 80 to 130 kn, set clearance altitudes from 150 ft and below, and obstacle clearance from 50 ft and below.

A partial flight test ground track from a representative TF mission is shown in Fig. 5a. Terrain following flight, or contour flight, is flown at constant heading between waypoints with only vertical maneuvering. The ground track of such flight results in straight lines between waypoints. A typical experimental flight test mission would begin at waypoint 2 in the northeast and follow a trajectory to the southwest to waypoint 9. After disengaging from the tracking of the trajectory, the pilot loops around waypoints 9–12, while the system is reconfigured for another test condition, and then flies another mission from waypoints 8–2. A TF/TA mission would cover the same waypoints with a meandering trajectory of vertical and lateral maneuvers. A typical 80-kn flight covers the 20-n mile course in about 20 min.

Complete flight test data from this representative TF mission in the Carlisle area are presented as the series of plots of Fig. 5. These figures trace the ground track (Fig. 5a) and elevation track (Fig. 5c), as well as the pilot's tracking of the guidance trajectory through the HMD symbology previously discussed. Lateral tracking is provided in Fig. 5b, and vertical in Fig. 5d. This TF mission was flown at a northeast heading at 80 kn airspeed. Set clearance altitude was 25 ft and obstacle clearance altitude 50 ft, for a combined clearance altitude of 75 ft. Expected guidance trajectory AGL clearances should be at 75 ft AGL and above.

The ground track plot of Fig. 5a presents both actual aircraft and commanded guidance position, although no difference is discernible at this scale. Horizontal navigation accuracy during this flight was 19.7 ft. Figure 5b traces the difference in the aircraft and commanded trajectories in this lateral dimension. Recall that the dimensions of the guidance trajectory troughs presented to the pilot through his HMD symbology (Fig. 2) are 200 ft at the top, 50 ft deep, and 100 ft at the bottom. (The commanded trajectory runs along the top of these troughs.) Hence, the pilot is within the confines of the trough width (± 100 ft) at all times. Mean lateral tracking was 13.7 ft, with standard deviation 22.8 ft.

The vertical flight profile of this same TF mission is shown as Fig. 5c. The upper solid line traces the aircraft MSL altitude while flying the guidance system with 25-ft set clearance altitude and 50-ft obstacle clearance height. The upper dashed line tracks the desired (or commanded) trajectory MSL altitude, which is that computed by the trajectory algorithm as modified by the forward sensor dependent path manager and presented to the pilot ($[\rho''_{traj}]$ of Fig. 1). The difference between these two lines, representing the pilot's vertical tracking of the desired trajectory, is given as Fig. 5d. The dash–dot line traces the guidance trajectory solution without the forward sensor enhancement. The lowest solid line of Fig. 5c is the truth measurement of the terrain elevation, which is calculated as the aircraft's MSL altitude minus the radar altimeter measurement. Vertical navigation error during this period was 26 ft, with radar altimeter error of $\sim$6 ft. Note that the radar altimeter generally measures height above the forest floor, not height above the treetops (canopy height). As such, the actual AGL height above the forest canopy is about 40 ft lower than shown here because of the average 40-ft tree height in this region of the test area, which was densely packed with trees.

The commanded (path manager corrected) pathway of Fig. 5c presented a smooth but aggressive trajectory of mean radar altimeter of 135 ft. Such AGL altitude is about 20 ft greater than predicted, given the 25-ft set clearance, 50-ft obstacle clearance, and 40-ft average tree canopy height (summing to 115 ft). Terrain undulations are clearly recognized and reflected in the pathway placement. Areas where the guidance pathway appears too high are most likely a result of local foliage effects, i.e., a tight, higher concentration of trees, or the effect of the smooth flight-path angle constraint imposed

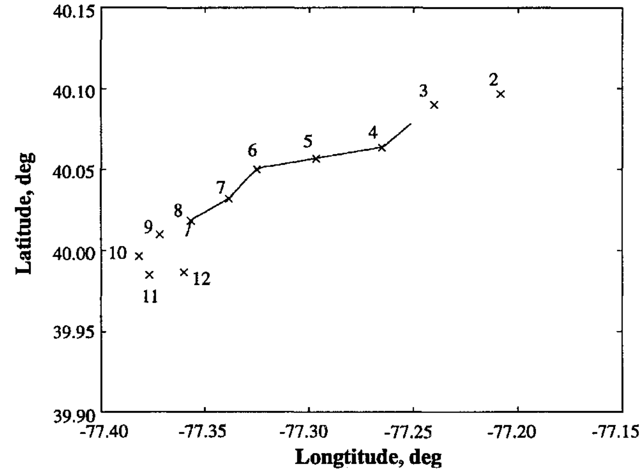

Fig. 5a Flight test ground track. TF Mission: 80 kn and 75 ft clearance altitude; numbers indicate course waypoints.

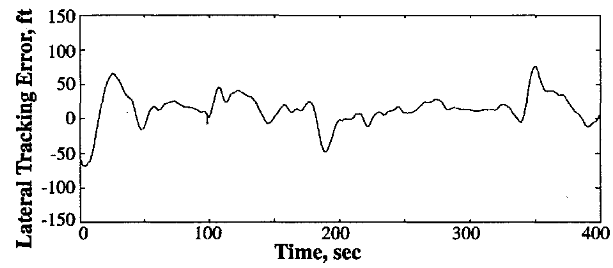

Fig. 5b Pilot lateral tracking of guidance trajectory. TF Mission: 80 kn and 75 ft clearance altitude; mean = 13.7 ft and std dev = 12.8 ft.

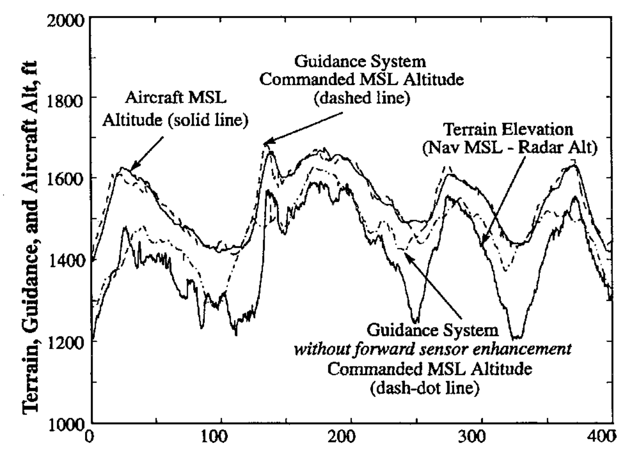

Fig. 5c Flight test elevation (vertical) track. Note that the terrain elevation calculation does not account for the tree canopy, approximately 40 ft higher. TF Mission: 80 kn and 75 ft clearance altitude.

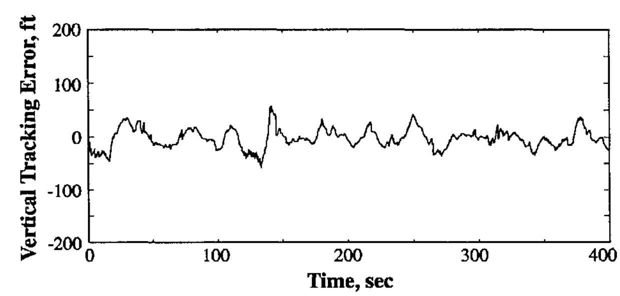

Fig. 5d Pilot vertical tracking of guidance trajectory. TF Mission: 80 kn and 75 ft clearance altitude; mean = −2.6 ft and std dev = 18.0 ft.

on all guidance trajectories. The flight-path angle constraint is the cause of the lack of lower descents into the valleys at $t \sim 250$ s and $t \sim 325$ s and the principal cause for increasing the mean radar altimeter clearance value. The section between $t \sim 150$ s and $t \sim 200$ s yields radar altimeter values between ~60 and 110 ft, representing the nearest tree canopy approaches during the flight.

The benefit of the laser radar forward sensor in vertically repositioning the guidance trajectory is clearly evident in Fig. 5c by comparing the guidance trajectories with and without the forward sensor enhancement. Without the forward sensor, the guidance system could not fly at such a low clearance altitude, as collisions with the ground would have resulted. The laser radar forward sensor, through the local obstacle database that it creates, supplies the necessary look-ahead information to extend the guidance system's flight envelope to this lower altitude.

Figure 5d traces the difference between the elevation (vertical) command position and that of the aircraft. Mean elevation tracking was −2.6 ft, with standard deviation of 18.0 ft. Except for the period surrounding the hill just before time 150 s, tracking is within the trough vertical bounds of 50 ft. Imperfect trajectory tracking can be traced to two principle reasons: the pilot can never track the symbology perfectly and at times will override the recommended pathway. Circumvention of the commanded trajectory occurs most often when a pilot shortcuts the suggested guidance trajectory, such as when a ridge is crossed followed by negative sloping terrain. This was the case in Fig. 5c when the ridge just before ~150 s was crossed.

Several manmade obstacles were also considered during the flight evaluation, including high-voltage wires at the Lakehurst course and towers at the Carlisle course. A fire tower of height 105 ft and adjacent communications tower of 220 ft, located at waypoint 2 of the Carlisle course, were routinely approached during the flight testing. The laser radar forward sensor was able to detect these towers and the wires at Lakehurst and caused a vertical adjustment of the guidance trajectory over the obstacle via the path manager integration described.

V. Discussion

Several lessons were learned regarding the forward sensor and integration technique. The system is very sensitive to the characteristics of the sensor generated database. Blending measurements using the maximum likelihood approach, the maximum elevation value for each grid and hybrids between these two were developed and implemented. The maximum likelihood algorithm calculates the elevation value for a particular grid that maximizes the probability of the elevation measurements to that grid, taking in statistical properties of the measurements known a priori.[10] This method has the advantage of drawing on all measurements recorded for a given grid cell but requires more computational memory and processing. Note that many other statistically derived state estimation schemes require the time at which each measurement was taken to be known (e.g., KF), a value that is not provided by the laser radar sensor. Because of the low number of forward laser radar sensor returns received for any given database grid element (typically only one or two per grid), the maximum value approach was favored for the majority of the flight testing. The use of the highest value detected by the sensor, however, for a given database grid did result in an excessively noisy database, which in turn generated a constantly shifting trajectory, unacceptable to the pilot for symbolic display presentation and unobtainable for pilot tracking. Efforts to address this noise vs obstacle sensitivity resulted in the use of the sequential vertical adjustment steps of the path manager described earlier.

It was also found that the pitch movement of the aircraft during the test flights would at times create azimuth swaths ahead of the aircraft where no sensor returns were recorded. This is a result of the fixed 25 × 50-deg FOV of the laser radar forward sensor. The effect was magnified whenever a hill was crested, further limiting the (relative) look-down ability of the aircraft sensor system. To address this problem, the dive angle limit for the trajectory was increased ($-10 \leq \gamma_{\max} \leq 6$ deg) to allow more aggressive pitch down maneuvers of the aircraft. This also addressed occasional ballooning of the guidance trajectory when cresting ridges.

The results from the flight tests demonstrate the lower altitude and obstacle avoidance capability added as a result of the forward sensor integration. Flight operations of the laser radar forward sensor guidance system to 75-ft AGL altitude for the speed range of 80–130-kn were demonstrated for the daylight VFR conditions flown. This AGL altitude is that combination of set clearance altitude for the nominal guidance trajectory solution plus that of the obstacle clearance altitude. Operation in similar flight envelopes in degraded weather conditions would be dictated by the ability of alternative forward sensors.

VI. Concluding Remarks

1) A wide field of view laser radar forward sensor was integrated into a low-altitude, terrain elevation based helicopter guidance system. The sensor's returns were used to generate an inertially referenced, aircraft-centered obstacle database. The baseline guidance trajectory was then altered to avoid terrain and obstacles along its path, allowing for reduced altitude operation, and adding an OA capability to the guidance system.

2) The forward sensor equipped system was implemented for real-time operation aboard a U.S. Army Black Hawk helicopter. The resulting guidance system was flight tested in both flat and moderately rugged terrain under a range of test conditions and obstacles.

3) Flight test results demonstrate the ability and benefit of a forward laser radar sensor to extend a low-altitude guidance system flight envelope to 75-ft AGL altitude and 80–130 kn flight in the presence of unmapped natural and man-made obstacles, during daylight VFR conditions.

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References

[1]Wendl, M. J., Katt, D. R., and Young, G. D., "Advanced Automatic Terrain Following/Terrain Avoidance Control Concepts Study," *Proceedings of the IEEE National Aerospace and Electronics Conference*, Inst. of Electrical and Electronics Engineers, New York, 1982, pp. 1366–1372.

[2]Chasteen, L., and Woodward, A., "Advanced Terrain Following Radar for LANTIRN," *Proceedings of the IEEE National Aerospace and Electronics Conference*, Inst. of Electrical and Electronics Engineers, New York, 1982, pp. 1277–1283.

[3]Cheng, V. H. L., and Sridhar, B., "Technologies for Automating Rotorcraft Nap-of-the-Earth Flight," *Journal of the American Helicopter Society*, Vol. 38, No. 2, 1993, pp. 78–87.

[4]Swenson, H. N., Zelenka, R. E., Hardy, G., and Dearing, M., "Simulation Evaluation of a Low-Altitude Helicopter Flight Guidance System," *Proceedings of the IEEE/AIAA Digital Avionics Systems Conference*, Inst. of Electrical and Electronics Engineers, New York, 1991, pp. 115–124.

[5]Nordmeyer, R., "Enhanced Terrain Masked Penetration Final Technical Report," U.S. Air Force Wright Aeronautical Labs., AF-WAL-TR-86-1079, Wright–Patterson AFB, OH, Sept. 1986.

[6]Zelenka, R. E., Yee, Z., and Zirkler, A., "Flight Test of Radar Altimeter Enhancement for Terrain-Referenced Guidance," *Journal of Guidance, Control, and Dynamics*, Vol. 18, No. 4, 1995, pp. 702–708.

[7]Zelenka, R. E.,"Design and Analysis of a Kalman Filter for Terrain-Referenced Positioning and Guidance," *Journal of Aircraft*, Vol. 31, No. 2, 1994, pp. 339–344.

[8]Holder, S., and Branigan, R., "Development and Flight Testing of an Obstacle Avoidance System for U.S. Army Helicopters," AGARD 2nd Mission Systems Panel Symposium on Low-Level and Nap-of-the-Earth (N.O.E.) Night Operations, Practica di Mare (Rome, Italy), Oct. 1994, pp. 19.1–19.10.

[9]Zelenka, R. E., Swenson, H. N., Dearing, M., and Hardy, G., "Simulation Development of a Forward Sensor-Enhanced Low-Altitude Guidance System," *Proceedings of the IEEE/AIAA Digital Avionics Systems Conference* (Ft. Worth, TX), Inst. of Electrical and Electronics Engineers, New York, 1993, pp. 267–275.

[10]Gelb, A., *Applied Optimal Estimation*, MIT Press, Cambridge, MA, 1984.