All Terrain Ground Collision Avoidance and Maneuvering Terrain Following for Automated Low Level Night Attack

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ABSTRACT

The development of an all terrain Ground Collision Avoidance System (GCAS) in conjunction with a "maneuvering" Terrain Following (TF) system is the focus of this paper. Both systems use a digital terrain database. These systems are presented concurrently because of their complementary mission role.

The unprecedented pilot interaction available with the automatic systems provides a means to significantly improve combat survivability. The pilot is able to execute high rate turns, evasive maneuvers, and inverted ridge crossings while following the terrain contour. Safety is maintained in day, night and weather by the ground collision avoidance system. The combination of these systems with an automated attack system, automatic target handoff system, night vision system, and a route planner to provide a lethal night attack capability is discussed. Piloted simulation and preliminary flight test results are presented.

INTRODUCTION

An increasingly dangerous air defense environment dictates the use of low level, high speed penetration tactics for air-to-ground attack missions. Terrain masking, terrain contour following, aggressive defensive maneuvering and night operations are needed for such missions. Safety in this environment, especially for a single-seat fighter, is a paramount concern. Current ground collision avoidance systems generally provide only warnings in limited cases. Conventional terrain following and terrain avoidance systems restrict the pilot's maneuvering capability. This can have an adverse impact on survivability when unknown threats appear. Pilot workload increases dramatically during night missions when advanced systems must be operated in addition to the tasks of navigation, attack planning, threat evasion, and target acquisition at extremely low altitudes. Automated integrated flight control systems are becoming more necessary and can provide safe and effective combat capabilities.

AFTI/F-16 PROGRAM

The Advanced Fighter Technology Integration (AFTI)/F-16 program is being conducted under the direction of the Flight Control Division within the Flight Dynamics Directorate at Wright-Patterson AFB in Dayton, Ohio. The prime contractor and developer of the all terrain GCAS and the "maneuvering" TF system is General Dynamics Corporation in Ft. Worth, Texas. Flight Testing is being conducted by the Air Force Flight Test Center with support from NASA Dryden at Edwards AFB, California.

The program objective is to flight demonstrate the benefits of advanced integrated systems for fighter aircraft. Specific objectives include testing technologies for Close Air Support (CAS) and Night Attack. Systems under evaluation include:

- All Terrain Ground Collision Avoidance System;
- Maneuvering Terrain Following System;
- Head Steerable FLIR/Night Vision System;
- Enhanced Sandia Inertial Terrain Aided Navigation;
- Automatic Target Handoff System;
- Pilot Activated Recovery System; and
- Silent Attack Radar Altimeter.

AIRCRAFT DESCRIPTION

The AFTI aircraft (Figure 1) is a highly modified F-16. Physical changes to the airframe include the addition of four

Based on a presentation at the 11th Digital Avionics Systems Conference, Oct. 5-8, 1992.
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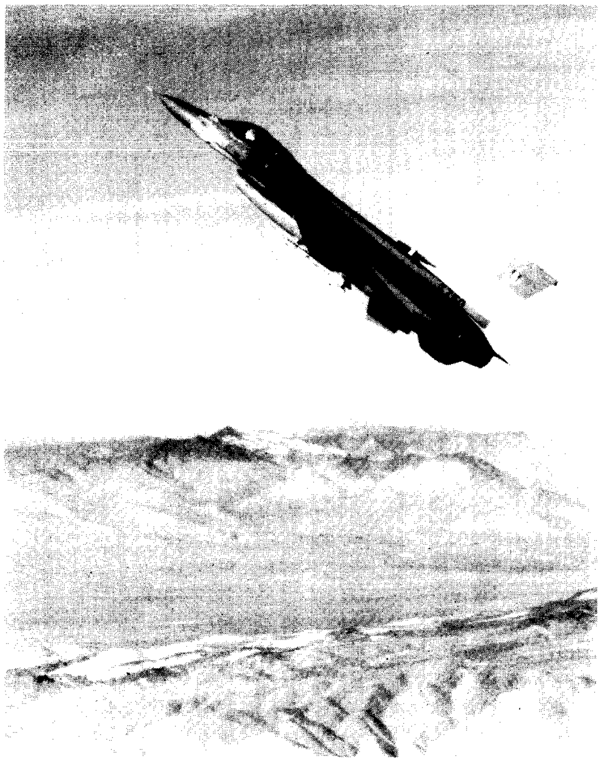

Fig. 1. AFTI/F-16 Aircraft

radar altimeter antenna pairs around the forward fuselage to provide altitude measurements at all roll angles (full 360 degree coverage). A dorsal fairing has been installed between the canopy and the vertical tail to house instrumentation and additional avionics. A Pave Penney sensor pod is conformably mounted in the left wing root and an inert pod is installed for symmetry in the right wing root. Internally the flight control system and avionics are a block 40 configuration. A Stored Terrain Access and Retrieval System (STARS) unit has been added to provide processing and storage capability for the terrain database related systems. A helmet mounted display system with integral night vision capability is installed along with the Falcon Knight navigation and targeting FLIRS.

TERRAIN DATABASE APPLICATIONS

The STARS accesses an on-board optical disc unit to retrieve digital terrain information from the database as required. The AFTI flight test database size is approximately 300 nautical miles by 300 nautical miles. The stored terrain information is derived from Digital Terrain Elevation Data (DTED) Level I provided by the Defense Mapping Agency. The STARS unit contains a shared memory area, input/output to the optical mass storage unit, a color display, an aircraft data bus, and five processor cards connected via a global bus. Each processor card contains a 1-MIP processor, read-only memory and local memory. The algorithms of both the all terrain GCAS and the maneuvering TF system execute on the same processor in the STARS. Also hosted in the STARS is a terrain referenced navigation system called Enhanced Sandia Inertial Terrain Aided Navigation (ESITAN). The ESITAN algorithm uses radar altimeter measurements and the terrain database to determine accurate aircraft position. An enhanced system altitude algorithm provides an unbiased aircraft altitude with inputs from ESITAN, the Central Air Data Computer, the Inertial Navigation System, and the radar altimeter.

ALL TERRAIN GROUND COLLISION AVOIDANCE SYSTEM

GCAS Background

During the Automated Maneuvering Attack (AMAS) phase of the AFTI/F-16 program, low level (200 feet), 5g automated curvilinear precision weapon deliveries were flown. This task was workload intensive due to the demands of the mission. An original "flat earth" GCAS system was developed in mid 1980's to allow the pilot to fly the AMAS mission while safely staying at or above a preselected minimum altitude. This "flat earth" GCAS system was designed to operate over terrain with a 2% grade or less. When required, it performed an automatic flyup maneuver. This maneuver prevented penetration of a minimum clearance altitude by rolling the aircraft to wings level and commanding a 5g pull.

A 1988 "readiness for transition assessment" concurred with the program test pilots and engineers that all terrain operation was essential for transition of the GCAS to the fleet. This need precipitated the current automatic all terrain GCAS system that is the subject of this portion of the paper.

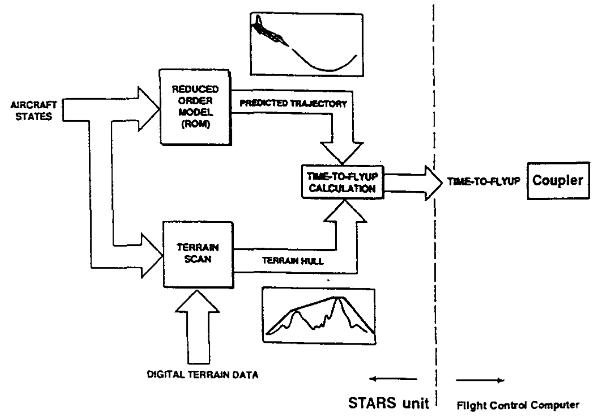

Fig. 2. All Terrain GCAS Functional Diagram

GCAS Design

The all terrain GCAS prevents penetration of a pilot selectable Minimum Clearance Distance (MCD) in any terrain, day, night, and in weather. As this system is based on the state of the aircraft rather than the status of the pilot, it will protect the pilot regardless of his condition.

Design requirements dictated that the system must have an adjustable minimum clearance distance function. It must use a digital terrain database. It must be non-intrusive and fail safe.

The All Terrain GCAS is functionally divided between the Digital Flight Control System (DFCS) computer and the STARS unit. The quad-redundant DFCS is responsible for producing the actual automated flyup commands, mode control, and integrity management. One of the STARS' processors is the host for the ground collision avoidance algorithm. The job of the ground collision avoidance algorithm is to compute the time-to-flyup and pass that information to the DFCS. The time-to-flyup is the time remaining before a flyup maneuver must be initiated to avoid penetration of the MCD. At time-to-flyup equal to or less than zero, the DFCS commands a flyup. The ground collision avoidance algorithm produces a new time-to-flyup 4 to 25 times per second. This continuous computation of the time-to-flyup provides for safe, accurate performance even when the aircraft is being flown aggressively. The mechanics of the flyup are discussed in the flight control coupler section.

The All Terrain GCAS system software is comprised of four parts (Figure 2). Three of these parts make up the ground collision avoidance algorithm: the reduced order model, the terrain scan algorithm, and the time-to-flyup calculations. The fourth part is the flight control coupler (Figure 2). Each will be discussed in detail in the following paragraphs.

Reduced Order Model (ROM)

The ROM is a mathematical model that resides within the ground collision avoidance algorithm. The ROM is used to continuously predict the aircrafts flight path based on its instantaneous dynamics. The ROM input states are normal acceleration, pitch and roll attitudes, pitch and roll rates, platform velocities, and air data. These states are used as initial conditions for each flyup trajectory prediction. From this point, estimators are used to generate the trajectory. The predicted flyup trajectory computed by the ROM is in two dimensions, altitude and distance.

From the initialized conditions, the ROM determines what the flyup couplers would command, and then applies those commands to produce new predicted aircraft states 0.2 seconds into the future. The trajectory is iteratively computed by applying the coupler commands to the last predicted states at each 0.2-second interval.

GCAS Terrain Scan Algorithm

The terrain scan algorithm has three major functions. First, the algorithm defines the appropriate scan region. Second, the algorithm reads terrain data from the digital terrain database, then sorts and filters the data. Finally, the data is "hulled," which is a further filtering process. These functions are discussed in greater detail below.

Defining the appropriate scan region is accomplished by first determining the location of the aircraft on the digital map and then scanning the correct quantity of digital terrain data. The terrain referenced navigation system, ESITAN, is used to position the aircraft on the digital terrain map. Aircraft dynamics including attitudes, velocities and normal acceleration are then used to determine the scan shape and quantity of data to pull from the locally stored terrain database.

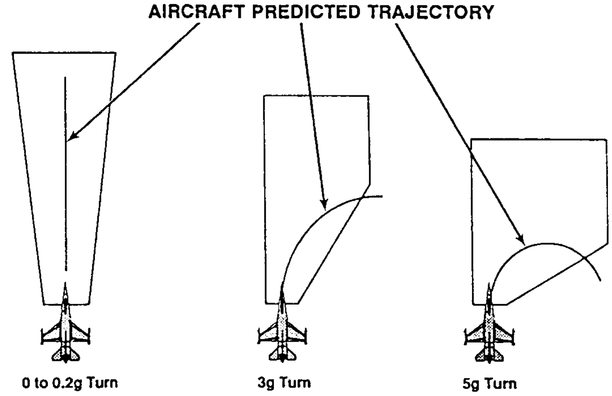

Fig. 3. All Terrain GCAS Scan Patterns

The shape of the scanned area is a polygon (Figure 3). The size and shape of this polygon is continuously updated to accommodate aircraft maneuvering, navigation uncertainties and digital terrain database errors. As shown in Figure 3, the scan pattern becomes wider and shorter as the turn becomes tighter and the normal acceleration increases. The design of this varying shape is a trade-off between ensuring that the appropriate terrain area is scanned to accommodate the aircraft's predicted flight path and minimizing the scan width to allow flight close to obstacles.

The highest terrain points from this scanned area are collapsed onto the two dimensional predicted trajectory that was computed by the ROM. A sorting process searches outward from the aircraft radially and places the collapsed points into sections called bins. The width of the bins can be varied to improve either throughput or terrain resolution.

Terrain data hulling is the process that is used to compensate for navigation uncertainty and errors in the terrain database. Hulling is the procedure used to connect the points in the two dimensional trajectory to form a representation of the ground. Hulls are always convex.

Time-to-Flyup Calculation

Using the aircraft's predicted trajectory and the information from the digital terrain database, a "time-to-flyup" is calculated. The "time-to-flyup" is the time increment remaining before the aircraft must initiate a recovery maneuver to avoid penetration of a pilot selectable minimum clearance distance. This clearance distance may be selected or changed at any time prior to takeoff or during flight, depending on mission requirements.

Flight Control Coupler

The AFTI/F-16 flight control coupler is responsible for, among other things, commanding the GCAS recovery maneuver. The recovery maneuver is a roll to wings level with a 5g pull (the g level is limited due to F-16 stores limitations). The roll to wings level is in the direction requiring the least time to accomplish and is g loaded once the aircraft is at a bank angle of 90 degrees or less.

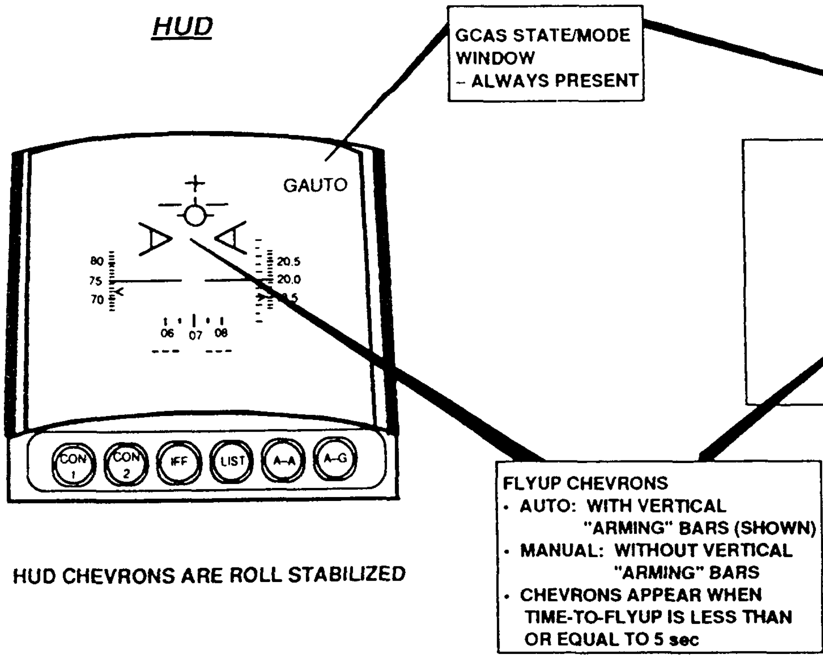

Fig. 4. All Terrain GCAS HUD & HMD Symbols

Pilot Interaction

The pilot may interact with the system in a number of ways. The system may be overridden by using the paddle switch on the stick. This action inhibits any automatic commands, during which the GCAS continues to compute but will not initiate an automatic recovery. When the pilot releases the paddle switch, automatic operation immediately resumes. The system may be disengaged with the activation of a cockpit switch or by using large stick forces.

The GCAS displays consist of a continuously predictive indication on the Head Up Display (HUD) and Helmet Mounted Display (HMD). When the time-to-flyup reaches five seconds, chevrons appear on the HUD and the HMD (Figure 4). The chevrons move inward as the time-to-flyup decreases, and the chevrons touch, forming a "break X," at zero seconds time-to-flyup. At zero seconds time-to-flyup, the system will automatically recover the aircraft. Additional pilot cues include voice messages, aural tones, and Multi-Function Display (MFD) indications.

GCAS Flight Test Results

To date, approximately 23 hours of GCAS testing have been accomplished during the CAS phase of the AFTI/F-16 program. The flyup maneuver itself, which was retained from the flat earth GCAS, has been tested almost 700 times. In the 23 hours of CAS testing, the MCD has been penetrated 3 times; each penetration was less than 10 feet.

Figure 5 illustrates a sample GCAS test run. The initial conditions for this run are 15 degrees of dive angle, 45 degrees of bank angle, and 470 knots calibrated airspeed. For this run the GCAS should recover the aircraft at an MCD of 300 feet. The top trace in Figure 5 is the aircraft flight path. The flyup

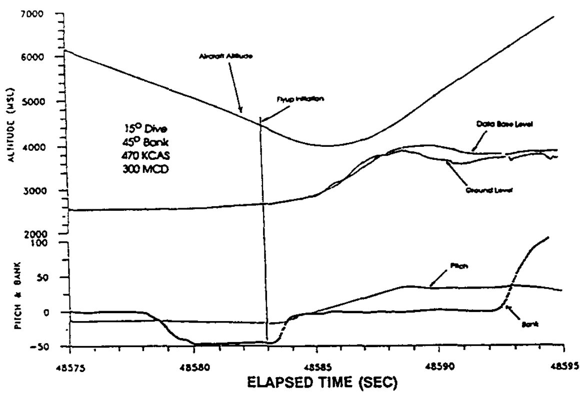

Fig. 5. All Terrain GCAS Flight Test Response

initiation line illustrated is the point at which the time-to-flyup is zero. As Figure 5 shows, the GCAS did recover the aircraft automatically at approximately 300 feet MCD.

MANEUVERING TERRAIN FOLLOWING

TF Background

Conventional terrain following systems place severe restrictions on aircraft maneuvering. These restrictions are imposed due to load factor limits, algorithm constraints, sensor stabilization considerations, flight path limits and ride quality requirements. In addition, a trade-off must be performed between the need to continuously change load factor for precise contour following and to restrict such changes for good ride qualities.

The necessity to detect the terrain ahead of the aircraft has previously required an active (limited scan pattern) sensor such as a forward looking radar. The problem of looking into turns and quickly resolving the terrain following trajectory calculations as the turn progresses is a challenge to conventional systems. Consequently, maneuvering constraints of 2 to 3gs and 60 to 70 degrees of bank angle are generally established for such systems. Furthermore, the required look-ahead distance for a radar of 8 to 10 miles is detrimental to covert operation.

TF Design

The maneuvering TF system developed for the AFTI CAS mission has design requirements of full maneuvering up to 5gs with unlimited roll capability. It was designed with a digital terrain database as the primary terrain input. Thus the system is unaffected by night operation, counter measures, or weather conditions. Once the aircrafts position is determined relative to the database, terrain features completely around the aircraft and along any predicted flight path are known. This allows the guidance algorithm to account for any possible maneuver thus removing the restrictions of radar based systems. A sensor is still needed for near field obstacle avoidance, but this requirement can be met with a CO_2 laser device of limited power and detectability or with a pilot assessing obstacles with NVG/FLIR devices.

Project pilots requested the ability, during automatic TF operation, to manually roll inverted over large peaks and ridges, aggressively pull down, and immediately transition back into automatic operation upon roll out. For the CAS mission, the pilots also requested a system that would perform vertical terrain contour following while maintaining a constant radius horizontal turn. In this way the pilot could automatically orbit (execute a terrain following circular path at 200 feet altitude) about the "initial point" awaiting air support instructions while continuing to be masked by terrain from ground threats.

A major thrust of the design was to provide a system that returned maneuvering capability to the pilot during the TF segments of the mission. The system was designed to be compatible with the AMAS, which requires a continuous g command for accurate weapon delivery. Such a continuous command during TF operation provides better ride quality while maintaining precise contour following.

Design requirements also included: a) minimizing deviations from the pilot selected set clearance plane without undershoots; and b) crossing peaks with zero flight path angle. The system had to provide commands to clear an obstacle 10,000 feet about the aircraft. In addition, a dive angle of 20 degrees and command limits of 5.0gs and 0.1g were imposed in the design.

The system consists of a terrain following algorithm, a flight control coupler, and system wide integrity functions. The terrain following algorithm includes a database scanning function, a critical point selection process, a trajectory generation method, and a guidance command generation technique. Each of these operations will be discussed in the following sections.

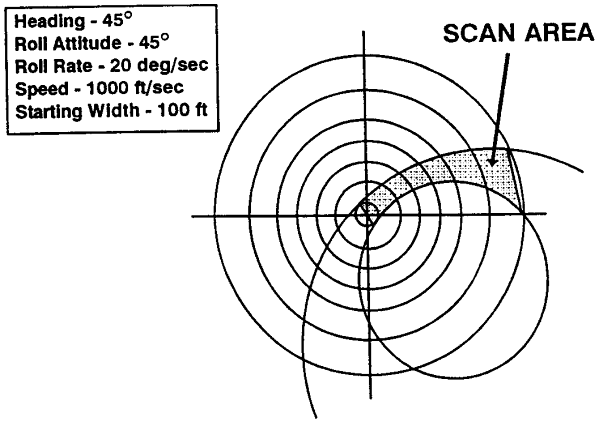

Fig. 6. Maneuvering TF Scan Pattern

TF Scan Patterns

The scanning function consists of determining the future flight path of the aircraft from present aircraft conditions such as load factor, roll rates, roll attitude, and airspeed. This projected flight path is calculated for approximately 8 miles ahead of the current position. Aircraft roll rate, load factor, and velocity are used to construct an inner and outer boundary about the projected flight path to account for the minimum and maximum turn radius that could be commanded by the pilot. Since a finite time is required to accomplish the scanning process, the future calculated flight path boundaries are expanded into a corridor to cover all the area the aircraft could overfly during the time needed for the scanning process. Navigation uncertainty, database errors, and database processing errors are taken into account by further expansion of this corridor to cover any area that could be beneath the aircraft when these uncertainties are considered. Range circles are defined to establish scan areas when combined with the flight path corridor as shown in Figure 6. The highest terrain point within each scan area is placed along the projected flight path to form a filtered 2-dimensional terrain profile.

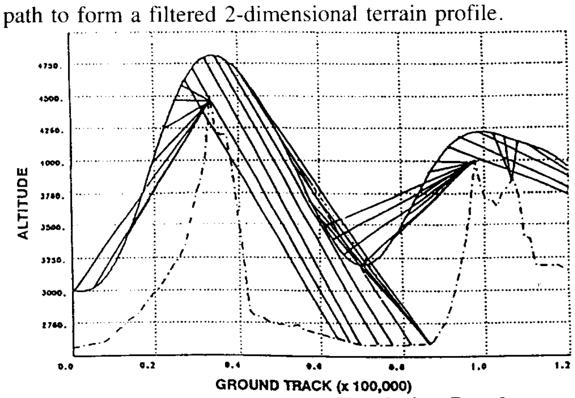

Fig. 7. Maneuvering TF Simulation Results

TF Critical Point Selection

The filtered profile is searched to determine critical points. Critical points are defined as points requiring the largest rate of change of acceleration for over-flight by the model of the

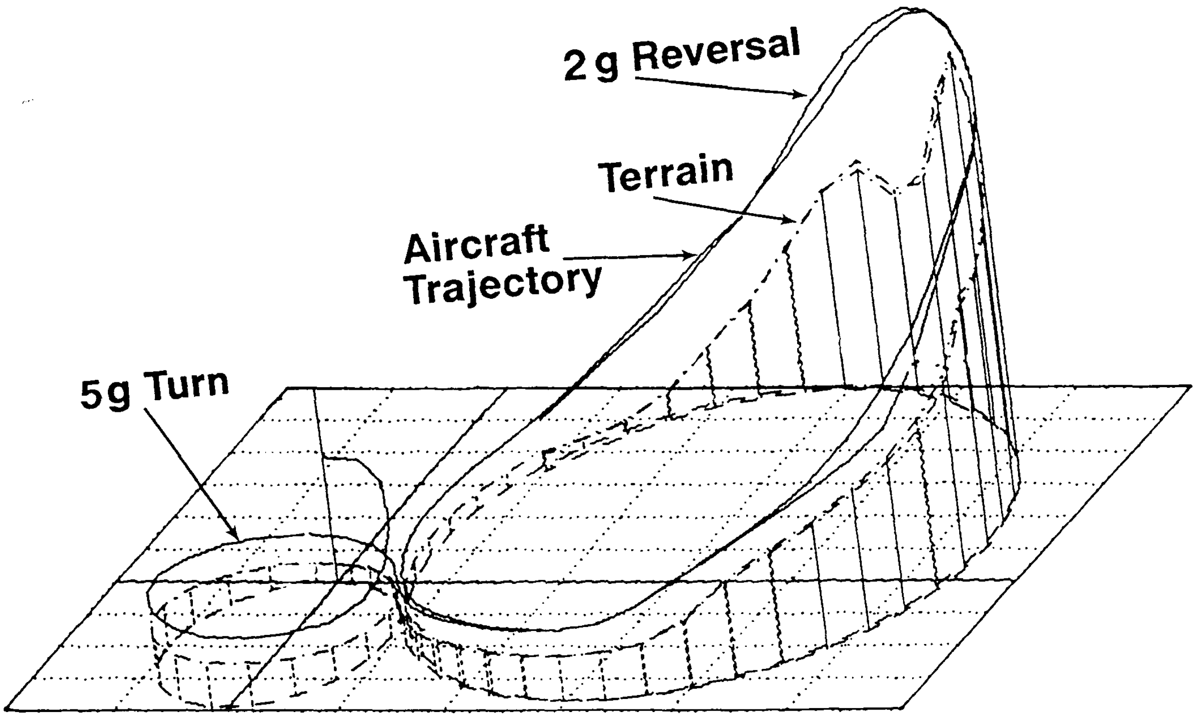

Fig. 8. Maneuvering TF Simulation Results

aircraft. This model is assumed to be on the previously computed flight path which is vertically coincident with the aircraft's present position. As shown in Figure 7, critical points are not exclusively prominent terrain features.

TF Flight Path Generation

A two point boundary value problem is solved with a Taylor series expansion curve fit to yield a trajectory for the aircraft model. The curve fit is established from the current aircraft model position to the critical point. The trajectory shape between points is affected by the ride quality requirements. Ride quality is pilot adjustable with soft, medium, or hard levels. The trajectory solution simultaneously satisfies ride quality, flight path angle, and g level boundary values. The curve fit is iteratively computed for each critical point as the aircraft travels forward. The algorithm easily accommodates rapidly changing flight paths. The coefficients for the trajectory solution for each critical point are used in a model following technique to generate guidance commands that will force the aircraft to follow the desired flight path. This trajectory solution is independent of aircraft position and therefore pilot blending does not change the established trajectory.

TF Command Generation

This algorithm uses the critical trajectory coefficients and acceleration limits to compute altitude, vertical velocity, and vertical acceleration commands for input to the control system TF couplers. This command generation nulls the error between the actual aircraft position and the position of the model following the flight path trajectory.

TF Limitations

TF operation is limited to the air-to-ground AFTI/F-16 attack envelope. In addition, the terrain referenced navigation system, ESITAN, must be in track and the All Terrain GCAS in the automatic mode. In automatic operation the system is restricted to ±89 degrees of bank. However, the TF cue in the HUD is appropriate for the pilot to manually roll the aircraft inverted to clear peaks and maintain the proper clearance. The system being flight tested does not have an active obstacle avoidance sensor incorporated. Provisions were included in the design for the fusion of terrain and obstacle information from multiple sources.

TF Simulation and Flight Test Results

Results from simulation for the maneuvering terrain following system are illustrated in Figure 8. A 5g turn is followed by a reversal into a 2g turn at 200 ft SCP. The aircraft is maintaining a 78.5 degree bank in the 5g turn and a 60 degree bank in the 2g turn. Initial letdown is accomplished from 900 feet AGL during the 5g turn. Small changes in both bank angle and load factor are commanded during the turns. The difference in the aircraft's trajectory during the second 2g turn is due to a slightly different ground track being overflown. The desired clearance is maintained in the turns and during the reversal. Figure 9 is flight test data from Edwards Air Force Base. This plot was chosen to highlight the differences that can be encountered between the digital terrain and the terrain measured beneath the aircraft. The system is performing well over what it believes is the terrain. The aircraft is at the SCP over the digital terrain database with zero flight path angle at the peak.

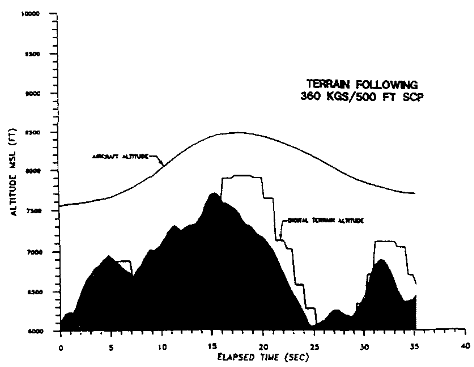

Fig. 9. Maneuvering TF Flight Test Results

NIGHT ATTACK SCENARIO

Figure 10 illustrates a night attack scenario. After takeoff, the aircraft is flown from steerpoint to steerpoint both around and over terrain automatically by the TF system along a navigation path determined by the inflight route planner. Target and friendly force information is data burst to the aircraft via the automatic target handoff system, loaded into the local digital terrain map, and used for intervisibility and threat calculations. At the Initial Point (IP), TF automatically drops off line and is replaced by the automated curvilinear weapon delivery system (AMAS). After automated weapon release, AMAS turns 180 degrees from the target and egresses. TF is reengaged for the remainder of the mission. The GCAS is engaged throughout the mission and has priority over any of the other systems.

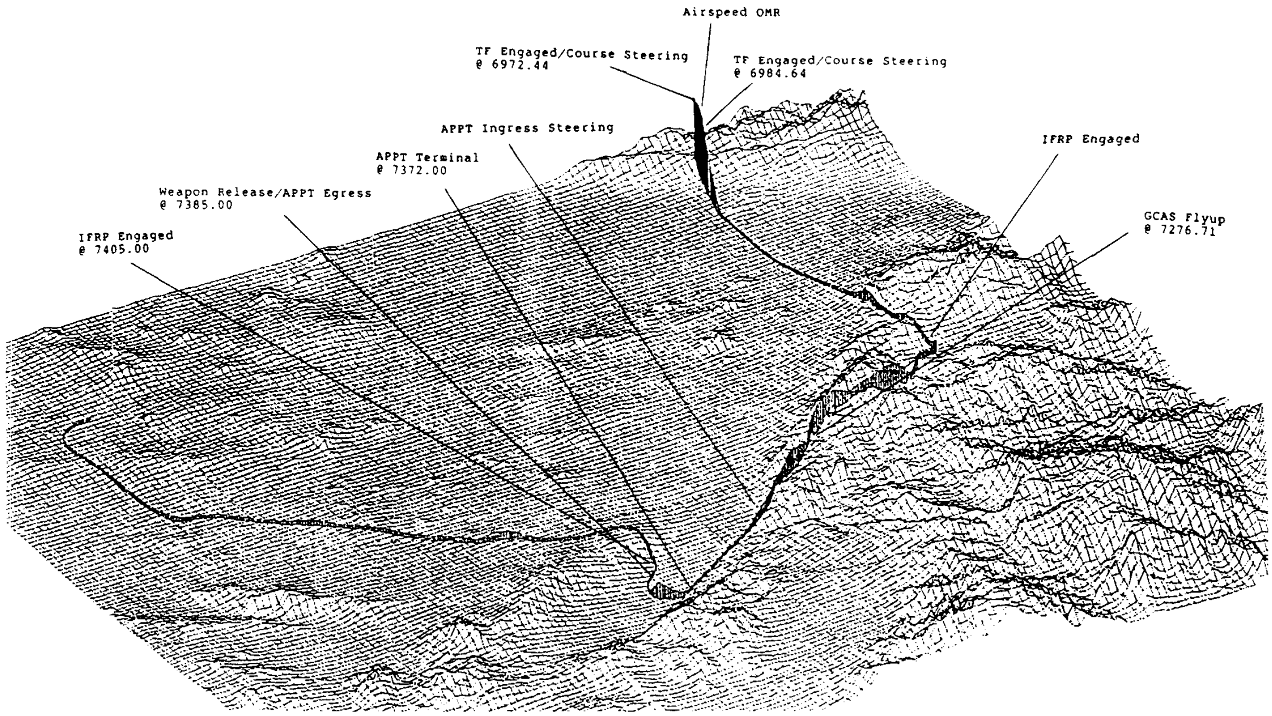

Fig. 10. Night Attack Mission

TF-GCAS COMBINED OPERATION CONSIDERATION

Even though the TF and GCAS systems were developed independently, consideration was given in the very early design phases to the impact each system would have on the other during combined operation. Given that the primary purpose of the TF system is to keep the aircraft as low as possible and the primary purpose of the GCAS is to keep the aircraft above a set altitude, it is easy to understand why initial simulations showed numerous nuisance GCAS flyups during TF operation. Modifications to the TF scan pattern to more closely model the GCAS scan pattern were the primary solution to the interference problem.

The illustrated night attack scenario depicts that a flexible, low level, low workload, night mission is possible using the GCAS and TF systems. The TF system minimizes the navigation task and keeps the pilot at the selected altitude. The GCAS maintains system safety.

FUTURE CONSIDERATIONS AND APPLICATIONS

There are several limitations that currently exist on the GCAS. Pitch attitude and altitude limitations are levied to preclude radar altimeter break-locks. Airspeed, both low and high, is limited because it was not needed for the close air support testing that AFTI is currently doing. Power approach was not investigated. Only a single store configuration was mechanized to demonstrate the concept. Modifications to the system mechanization can be made to eliminate these restrictions. The TF system has worked well to date. It does not, however, have the capability to detect and avoid obstacles. A necessary addition for operational use is the integration of the TF algorithms with a forward looking sensor that can detect obstacles.

SUMMARY AND CONCLUSIONS

The GCAS is sufficiently mature to transition for operational use. The TF algorithm works well, but flight testing is incomplete. In addition, an obstacle avoidance capability needs to be integrated with the TF system. This could be provided by a forward looking sensor, such as a CO_2 laser, or an advanced NVG/FLIR device.

These two systems can provide improved mission flexibility and immunity from controlled flight into terrain. They reduce pilot workload and allow the pilot to concentrate more on mission objectives. As cockpits and missions become more complex, systems such as the TF and GCAS described in this paper must be fielded.

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Finley has been active in control system design and analyses for over 20 years. He was instrumental in programs to develop digital fly-by-wire control, integrate flight and fire control systems, control configured vehicle design methods, and nonlinear control techniques.

Currently, he is engaged in research involving advanced integrated control applications. He is a consultant for several flight test programs within the Directorate including the Advanced Fighter Technology Integration F-16 Close Air Support program, Variable Stability In-Flight Simulator program, and the Multi-Axis Thrust Vectoring program. Finley is also acting as the Integration Technical Lead for the Propulsion Aerodynamics Control Integration R&D program.

Judi Probert is a flight control engineer in the Flight Control Division of the Flight Dynamics Directorate at Wright-Patterson Air Force Base in Dayton, Ohio. She graduated from Drexel University with a degree in mechanical engineering in 1985. In 1989, Judi received a master's degree in aeronautical and astronautical engineering from Purdue University.

Judi is currently the lead flight control engineer for the AFTI/F-16 program. In addition, she is the program manager for the Strategic Flight Management Program and is the flight management engineer for the Artemis Precision Strike Program.