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TESTING OF AN AUTOMATIC, LOW ALTITUDE, ALL TERRAIN GROUND COLLISION AVOIDANCE SYSTEM

John Fergione, Test Pilot, Lockheed Martin Tactical Aircraft Systems, Ft. Worth, Texas
John Weigelt, Chief Flight Operations, Computer Sciences Corporation, Edwards AFB, California
Michelle Baldonado, Project Engineer, 416th FLTS, Edwards AFB, California
Jay Welch, Flight Test Engineer, Lockheed Martin Tactical Aircraft System, Ft. Worth, Texas
Edward Griffin, Avionics Engineer, Lockheed Martin Tactical Aircraft Systems, Ft. Worth, Texas
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Abstract

The expansion in the number of low-altitude flight operations, along with increased pilot workload, have made controlled flight into terrain the number one cause of loss of aircraft in the United States. The Automatic Ground Collision Avoidance System (Auto-GCAS) program attempted to provide a system to eliminate that cause of aircraft loss. Although a similar, less sophisticated system had previously flown on a research F-16 aircraft, these tests would involve a more refined system and would be accomplished on a production representative F-16D aircraft. The processes that took place to actually conduct these tests were lengthy and complex. The objective of this paper is to give an overview of those processes and how they eventually led to a successful flight test. The major taskings that will be discussed are: the modification of the aircraft; the development of the mobile control room; the test plan and safety review process; test conducting; and the pilots perspective of the actual flight operations.

Introduction

From the flight test perspective, the program began when the Air Force Flight Test Center (AFFTC) at Edwards AFB, California, received the Program Introduction Document from the Air Force Research Laboratories in Dayton, Ohio. This document provided the overall requirements for the program. Once the Program Introduction Document was in-hand, a test concept meeting was convened to define the responsibilities of the numerous organizations involved in the test process. From that meeting the various disciplines started working their areas of responsibilities.

Modification of the Aircraft

The first task to be completed was modifying the test aircraft. The aircraft used for the Auto-GCAS program was a highly-modified, two-seat F-16D aircraft. With today's advances in Inertial Navigation Systems (INS), Global Positioning Systems, Terrain Referenced Navigation (TRN) systems, and Digital Terrain Systems (DTS), coupled with enhancements to the Digital Flight Controls Systems (DFLCS), the implementation of an Auto-GCAS required only minor modifications to the F-16D test aircraft. Although these modifications included small hardware changes, the most substantial modifications occurred in avionics and flight controls operational flight software.

Hardware Modifications

Implementation of Auto-GCAS on the target aircraft required only two minor hardware changes. These changes consisted of a wiring change to the DFLCS and the replacement of the data transfer unit (DTU) with the upgraded data transfer unit (UDTU). The wiring change consisted of rewiring an existing switch to provide another discrete input to the DFLCS. This switch gave the pilot the ability to initiate the auto fly-up function of Auto-GCAS. Additionally, the UDTU was added to provide the processing power needed for the terrain management and scanning functions. Since the UDTU power requirements and interfaces are identical to the DTU, no additional aircraft modifications were required for installation.

Software Modifications

The Auto-GCAS effort required software modifications to several of the F-16D subsystems. These modifications included Auto-GCAS design implementation, along with flight test safety and evaluation requirements. The affected subsystems consisted of the general avionics computer (GAC), heads-up display (HUD), up front controls (UFC), voice message unit (VMU), UDTU, data transfer cartridge/Digital Terrain System (DTS), and DFLCS.

The GAC performed the weapon delivery, navigation, energy management, fault reporting, master mode control, and submode control functions, along with providing serial-digital bus control for four 1553 multiplex (MUX) buses. In addition to bus control and fault reporting modifications, changes were made to distribute

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Auto-GCAS mode/submode, minimum descent altitude (MDA), stores loading, and other Auto-GCAS related information to various aircraft subsystems.

The HUD displayed flight data symbols representing attack, navigation, weapon aiming, and landing information, along with essential aircraft performance data such as altitude, airspeed, attitude, and heading. New symbology and text windows were added to the HUD to support Auto-GCAS flight test requirements. Three text windows were added to display Auto-GCAS modes/submodes, Auto-GCAS status, and air speed warnings, while a visual queue was added to provide the pilot with an indication of when the time until penetration is predicted to be less than a pilot entered time.

During Auto-GCAS flight testing the HUD display was transmitted to the control room. Therefore, in addition to providing the pilot with essential information about the Auto-GCAS, the new symbology and text windows were monitored real-time in the control room, along with other data, to assess the status and performance of the system.

The UFC provided primary communications, navigation, and identification control and display of various aircraft functions. Modifications to the UFC allowed the pilot to select and deselect Auto-GCAS and Auto-GCAS submodes, enter MDA, and enter a variable display time for a visual queue. Since the UFC display was displayed in the HUD, these data were also available to the control room for real-time monitoring.

The VMU provided the pilot with aural warnings, cautions, and advisories of critical aircraft functions. Three messages were added to the VMU to provide the pilot with aural messages indicating an auto fly-up has occurred, an auto fly-up has terminated, and air speed is too low to support an auto fly-up maneuver.

The UDTU was essentially an enhanced DTU. It provided automatic file management, data entry, and data retrieval capabilities, along with housing the DTC/DTS. Replacing the DTU with the UDTU provided a cost effective means of obtaining the additional processing power required for Auto-GCAS-specific algorithms. Since the UDTU offers all the capabilities of the DTU, plus a 32-bit processor, expanded memory, high speed access to the DTC/DTS, and expanded 1553 MUX interfaces, additional capabilities were added without sacrificing existing ones.

Once integrated into the avionic suite, several modifications were required to support Auto-GCAS. Among these were the addition of terrain management and scanning functions. The terrain manager maintained a local digital terrain map which was used by the scanning algorithm to produce a two-dimensional terrain profile for use by the aircraft response model (ARM).

Eight data pump blocks, containing flight critical and performance data, were added to the 1553 MUX interface. Selected data in these blocks were transmitted to the control room during the flight testing for real-time monitoring of the system.

The DTC/DTS was a transportable mass memory cartridge with a high-performance signal processor which is housed in the UDTU. The current configuration of the DTC contains both the DTS and the TRN systems.

The DTC/DTS was modified to host the ARM. The ARM predicts a flight trajectory based on different flight conditions and compares it with the terrain profile from the scanning algorithm to determine if a fly-up is warranted.

The DFLCS calculated control surface commands for the aircraft to provide stability, handling, and control. Several software modifications were required for Auto-GCAS implementation and flight test safety. These modifications included the Auto-GCAS coupler, Auto-GCAS modes, and System Wide Integrity Management (SWIM).

The Auto-GCAS control laws were integrated into the F-16D coupler to provide the recovery commands for the auto fly-up maneuver. Auto-GCAS mode logic was added which supports five modes, OFF, FAILED, STANDBY, ACTIVE, and FLY-UP. The SWIM was incorporated to monitor INS, fire control computer, radar altimeter, and UDTU for fault information. Four data pump blocks, containing flight critical and performance data, were defined and were available on the 1553 MUX interface. Selected parameters contained in these blocks were transmitted to the control room during the flight testing for real-time monitoring of the system.

Mobile Control Room Development

A parallel effort to the aircraft modification was the development of the mobile control room. Evaluating the performance of the Auto-GCAS necessitated flying over a variety of terrain. Among the more critical evaluations were those calling for the aircraft to fly against a peak in excess of 6,000 feet with a vertical rise of less than 60 degrees. The closest terrain that met those requirements was located in the Sierra Nevada mountain range over 100 miles north of the existing fixed telemetry and ground control facilities at Edwards AFB, California. That distance, plus the low altitude at which the aircraft would be flying, placed it well out of range of the Edwards facility. To overcome this problem, a mobile telemetry and ground control room system was developed.

Initial Activities

Two ground launch cruise missile control vans were acquired through the U.S. Air Force. One unit was designated for use as the front-end or telemetry van and the second unit became the control room van. These units were stripped of equipment and delivered to the Ridley Mission Control facility at Edwards AFB, California. Additionally, two ground launch cruise missile tow vehicles were also procured. These all-terrain six-wheel drive vehicles were capable of towing the control and telemetry vans in areas where roads were unavailable.

Once the vans were in-hand, the first priority was to ensure adequate power and air-conditioning would be available to support the installed electronics. It was determined that the power and air-conditioning units that came as original equipment were either unsuitable for our use or unsupportable, thus it became necessary to replace them. The air conditioners on each van were replaced with 5-ton units and new 30 KVA diesel generators were installed.

Once the external modifications were completed and the electronics and other equipment installed, the vans were repainted from their original camouflage paint scheme to white. This served two purposes: it made them more visible from the air and helped to keep them cooler in the desert environment in which they operated. This significantly reduced the air-condition loads. The tow vehicles retained their original camouflage color.

Completing the two-van operation was a dual-axis (azimuth and elevation), 8-foot parabolic dish capable of receiving signals in the 1.4 to 2.4 ghz range. This antenna was mounted on a trailer allowing it to be towed behind a light utility vehicle. Once at the deployment site, the towed antenna as connected to the telemetry van where it was controlled by the telemetry engineer.

Telemetry Van

The telemetry van provided the front-end processing for the two received telemetry streams (video and selected multiplex parameters). The right and left hand circularly polarized telemetry streams were sent from the antenna into the telemetry van where they fed into a multicoupler. The multicoupler split the signals and fed them into receivers where the data were stripped from the carrier signal. The output from the receivers, in the form of a square wave signal, was fed into combiners which compensated for any polarization caused by aircraft maneuvering. From the combiners the signals were fed into bit sync units which conditioned the signals and synchronized the data to a clock pulse. The signals were then decrypted---the pulse coded modulation (PCM) data going to the O/S 90 processor and the video signal to the video decoder. In the case of the PCM data, the O/S 90 decommutated the telemetry data into individual parameters, then sent it to the universal memory network for distribution into the control room van. In the case of the video signal, it was sent to a video decoder which removed any compression algorithms, converted the digitized video into National Television Standards Commission video format, then sent it on to the control room van.

One of the stations in the telemetry van was assigned to the telemetry engineer who controlled the tracking antenna. The telemetry engineer had a video link to a camera mounted on the antenna that allowed him to optically acquire the test aircraft. Once the test aircraft was acquired optically, the telemetry engineer switched tracking to the automatic function and the antenna tracked the aircraft using telemetry signal strength. Also contained in the telemetry van was the equipment used to record the PCM data stream, the HUD video, and the antenna tracking video.

Control Room Van

From the universal memory network in the telemetry van, the two data streams were fed via fiber optic cables into another universal memory network in the control room van. From there they were distributed to the various stations.

The control room housed positions for six personnel: the test conductor, the test director, three control room engineers, and a data analyst. With the exception of the data analyst, each position had a 13-inch video monitor where real-time HUD was monitored. These monitors served as a back-up to the data displays where critical parameters were monitored. Four strip charts were installed and recorded a time history of altitude, airspeed, and dive and bank angles. These were not actively monitored during flight, but were used for postflight analysis. One control room station was equipped with a scan converter and super VHS video recording equipment to allow video taping of the computer generated displays at that location. Primary communications to the aircraft was with an ARC/164 UHF radio that had been adapted for ground use. A modified RT-1319B/URC digital programmable UHF and VHF radio was used for back-up communications.

The Test Plan and Safety Review Process

The defining documents required for flight test at the AFFTC are the test plan and the safety review process, both of which are the responsibility of the project engineer.

Test Plan

Test plan development began at the same time as the aircraft modification and the control room development. This document included all the test objectives outlined in the Program Introduction Document and defined the whole test process. It provided a background of the project, identified the resources required to conduct flight tests, provided the methods of test and evaluation, identified the analysis procedures, as well as describing post-test reporting requirements and all logistics requirements. Unquestionably the heart of the Test Plan was the test point matrix.

Once the test plan was complete, a Technical Review Board (TRB) was convened at which the Auto-GCAS project manager presented the plan to a panel of experts not intimately associated with the project. Key members of this board were the flying qualities and avionics representatives from the AFFTC. Also in attendance was the project pilot. The purpose of this board was to review the plan for technical adequacy and practicality.

Once the technical aspects of the test plan were agreed upon by the members of the Technical Review Board, and the recommended changes incorporated into the test plan, the plan was incorporated into the safety package, where during the safety review process, it would again be reviewed for safety considerations.

Safety Review Process

The safety review and approval process for the Auto-GCAS flight test was a formal process known as the Safety Review Board (SRB). During the SRB the same members who participated in the TRB, along with the Unit Test Safety Officer and the AFFTC safety representative review numerous documents for safety considerations.

Prior to the official SRB, considerable time was spent reviewing past projects for safety implications. The Auto-GCAS which was tested had evolved from a navigation system that had previously been tested, plus it was combined with an automatic aircraft response model which was a direct result of a system that has been under development for the past 12 years. The test team felt confident in the ability of the system to allow the pilot to perform his mission, to know the aircraft's position with respect to the ground, and the system's ability to respond to avoid ground collision.

Minimizing procedures from previous similar projects were reviewed and new ones developed specifically for this test. For example, the test team designed each test maneuver to suit the design specifications which included the results from simulator testing. Each maneuver and test card was briefed in detail for each individual mission to the test pilot and control room personnel. Each maneuver that was evaluated was written on a test card which included detailed aircraft conditions and procedures. Specifically for Auto-GCAS flight test, minimum conditions were included, which when reached, will result in control room personnel directing that the run be aborted. Some of these conditions were altitude, airspeed, dive and bank angle limits as well as system status.

Once all safety implications were reviewed, the SRB was convened by the safety office at the AFFTC. The safety documents reviewed included a condensed version of the project description, the test objective, the test item description, the system maturity and how it related to previous systems and tests, the types of tests that were done, records of the technical review and safety review procedures, accountability procedures for mishaps, minimizing procedures to prevent mishaps, as well as the test plan itself.

At the SRB meeting, the safety documents were presented and a risk assessment was made based on the conditions put forth in the test run matrix. Once the safety document had SRB approval and a risk assessment for each test point determined, the document was forwarded sequentially through the chain of command. Safety plan approval for the Auto-GCAS project required the signatures of the AFFTC Director of Safety, the squadron commander, the test wing engineer, the group commander, the test wing commander as well as the AFFTC Commander.

Once the AFFTC Commander signed and approved the safety document, the test plan was ready to fly and all the procedures defined by the safety plan document were adhered to during flight test. The final safety worth of our methods of minimizing mishaps during flight test was a measure of the combination of the test teams knowledge of the aircraft and the Auto-GCAS, the pilot's input to the system, and the control room process.

Test Conducting

Once the test plan was finalized and the safety process underway, the activities of the test conductor began in earnest. Of prime importance to the test conductor was the test run matrix portion of the test plan. It was from this document that all mission test cards would be written and the actual conduct of the flight test would occur.

Mission Cards Preparation

During the test safety process, test points identified in the test matrix were categorized as either low risk or medium/high risk. While low risk testing did not require ground control monitoring as there were no unique hazards present, it was nevertheless the practice during this project to actively monitor all flights, not just those identified as medium and high risk. For medium and high risk test flights requiring positive control, i.e., point-to-point clearance, mission control facilities were required to monitor real-time displays, identify system anomalies, and reduce the probability of encountering potential hazards. The Auto-GCAS test run matrix had a tota of 334 test points of which 76 percent were considered low risk, 13 percent medium risk, and 11 percent high risk testing.

The test card package provided to the pilot was made up of four sections. The first section was the cover page which listed each individual medium or high risk card within the package. The second section showed technical aircraft information, i.e., aircraft configuration, mission frequencies, aircraft g limits restriction, and weight and balance calculations. The third section informed the test pilot on system operation limits, special instrumentation set-up, and critical aircraft switch setting required for test, and the fourth section were the actual cards identifying the test points the pilot would fly.

From the test point matrix, the flight cards were prepared in an organized logical mission flow, using an incremental build-up procedure, progressing from the lowest risk to the higher risk flight test condition for the objective being evaluated. The test conductor was required by regulation to brief medium risk test flights the day of the flight to numerous people up the chain of command. These included the: project engineer, flight commander, operations officer, squadron commander, group commander, and the test pilot. High risk test flights required a 24-hour pre-brief and approval by the same personnel as well as the test wing commander. During this briefing, the risk level on each test point was identified as well as what type of minimizing procedures was used to reduce pilot risk. Once the test cards were signed by the appropriate reviewers, actual conduct of the flight test was ready to begin.

Test Mission Conduct

The test conductor presided over a mobile control room that provided telemetry coverage using state-of-art real-time displays and data processing. Special instrumentation had been added to the aircraft to allow control room personnel to monitor real-time critical safety-of-flight parameters for this program. The two major systems used to enhance pilot safety were the use of telemetry aircraft video of the HUD, and the Internal Advanced Ranging Data System (ARDS). Telemetry of the aircraft HUD allowed control room personnel to view, real time, aircraft system's performance and operation. The ARDS was an independent aircraft position system installed internal to the airframe and was used as a second navigation system to compare aircraft position.

The control room was an area comprised of instruments that displayed real-time aircraft information to personnel. Radio communications between and the pilot and the test conductor allowed control room personnel to monitor the sequence of flight test, the status of the system before each run, and very closely monitor aircraft conditions and system status throughout the maneuver. A method of monitoring the test maneuver was used that allowed personnel to monitor Auto-GCAS status, time before recovery, altitude, dive angle, airspeed, and bank angle for cases where the pilot exceeded the design limits and needed to be prompted to manually initiate a recovery. When that occurred, the individual monitoring that specific parameter called out "abort, abort, abort" and the test conductor relayed that message out to the pilot. Results from this method were that the pilot responded with a manually initiated recovery or "fly-up" within less than 1 second of the call.

This timely response to abort calls was further enhanced by the fact that, once the aircraft was ready to start the test run, the test conductor instructed the pilot to execute an abort for "any" radio call. This was further protection to the pilot against radio chatter and now made the test pilot ready to react to any abort call.

The Test Pilots Perspective

It was apparent from the start that flight safety was a great concern. The airplane was going to be placed at risk and the test pilot was going to have to throw comfort aside and let the airplane get closer to the ground than was preferable. Preparation of the test team would be a requirement, as merely relying on the pilot's ability to prevent ground impact would not be sufficient to allow the test to proceed. Confidence in the automatic system would hopefully develop as the test progressed; however, building up to more and more extreme flight conditions would have to be done safely. Safety had to be the primary consideration during the data acquisition phase.

The F-16 simulator in Ft Worth, Texas, was used primarily to refine the test run setup, abort altitudes, and minimum altitudes at which the pilot would manually recover the airplane. This simulator contains the Edwards AFB local flying area terrain database; thus, runs could be flown exactly as they would be when test flying commenced.

Simulators are great tools, however, they also have limitations. Obviously, impacting the ground is not a life threatening concern to the test pilot in a simulator, though this occurrence would be looked upon as a fault in the system, which certainly needed to be corrected. Nonetheless, having the capability of flying all of the hazardous runs repeatedly, in a nonthreatening environment, allowed for an early cursory evaluation of the system. The results would become invaluable flight briefing items.

The visual display resolution also had drawbacks. In this type of test, "ground rush" later became one of the largest factors in evaluating whether a ground proximity fly-up was a nuisance or not. A nuisance fly-up is defined as a fly-up which occurred too early in the pilot's view. The ground rush cues could not be simulated because of the visual display limitation. The limitation, however, was not considered a serious drawback as the simulator had many other advantages that over-shadowed this. The simulator would thus be used solely as a tool primarily to evaluate the engineering models in the system. Pilot perceptions would have to be restricted to the test-flying phase.

The simulator matched the airplane's performance closely. The test pilot, nonetheless, had to be continually aware that the inability of the simulator to provide g force cues would have to be taken into account for test run setups. Runs, which could be flown at extreme negative or positive g forces in the simulator, would not be practical later. The test pilot thus had to fly the simulator exactly as he would later fly the airplane. The easiest way to do this was to note the starting altitude, set the airspeed and bank angle conditions and then allow the airplane to descend at somewhere between 0 and 1 g. The starting altitude could then be adjusted up or down so that the desired dive angle was reached at fly-up commencement. The altitude was then brought to the flight briefing so that numerous repeat runs would not have to be flown in flight. In this regard, the simulator was useful and allowed the pilot to get the desired data without a lot of inefficient time in the airplane. It also allowed the control room personnel the ability to confirm test run setup with the pilot during the flying phase prior to each run being flown.

Since close proximity to the ground would occur on the first test flight, it was particularly important the control room personnel be experienced and work as a team. The F-16 simulator proved to be a great tool for providing the test team with the necessary experience to conduct the Auto-GCAS test. Test runs were flown in the simulator as close to how they would later be flown in flight as was feasible. This practice allowed for immediate debriefing, when necessary, and allowed the individual participants, including the test pilot, to voice their views and alter the team's procedures as often as was deemed necessary. The time spent at this would prove invaluable later. On first flight, every member knew not only their responsibilities, but also what to expect from everyone else. Flight test safety was maximized as a result.

Throwing one's self at the ground in the hopes that the airplane will behave properly is far from a natural act. To fly in at low altitude and high speed and then roll the airplane inverted and "just let go" is something only a few pilots have ever done and, hopefully, none have ever considered doing. Likewise, flying the airplane in a 90-degree dive at 0 g until fly-up knowing the minimum descent altitude was going to be low is just not fun. The most uncomfortable runs were, by far, those flown at shallow dive angles and large bank angles against flat terrain. It took a lot of self-discipline and confidence in the control room to not "help" the airplane with its automatic recovery. Confidence in the control room was certainly a requirement. The simulator, again, helped greatly to achieve this, as the pilot gained this confidence while working with the control room in developing the test procedures. the buildup runs in flight also helped to confirm and solidify this confidence. Without this, the data gathered would probably not have been as useful as was required.

Conclusion

Flight testing even the most basic system is an involved and complex process involving many disciplines. In the case of the Auto-GCAS program, it proved an even greater challenge due to the unique requirements of testing against remote mountainous terrain under medium and high risk conditions. The development of the mobile control room proved invaluable, not only for providing a means to accomplish the remote testing, but for ultimately providing an asset for use on future AFFTC programs. Of equal importance were the efforts put forth in the area of safety. The safety review process, plus the extensive simulator training for pilots and control room personnel at Ft. Worth, Texas, proved to be a highly rewarding effort. The reduced risk to both the pilot and aircraft were directly attributable to these efforts. With the successful completion of the Auto-GCAS project, sufficient data is now available to assess the viability of this system to prevent aircraft and aircrew losses due to controlled flight into terrain.