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RESULTS OF A JOINT US/ SWEDISH AUTO GROUND COLLISION AVOIDANCE SYSTEM PROGRAM

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Abstract

This paper documents the results of the development of an Automatic Ground Collision Avoidance System (Auto GCAS) for a fighter aircraft. This development effort is a joint United States and Sweden program. Auto GCAS technology is being considered for application on the F-16 and JAS39 aircraft pictured in Figure 1. The United States part of the team consists of Advanced Fighter Technology Integration/F-16 or AFTI/F-16 personnel. This includes members from the Air Force Research Laboratory at Wright-Patterson AFB, the Flight Test Center at Edwards AFB, NASA Dryden, and Lockheed Martin Tactical Aircraft Systems in Ft. Worth. The Swedish part of the team consists of personnel from Försvarets Materielverk in Stockholm and Saab in Linköping.

The design utilizes a digital terrain system with a terrain referenced navigation algorithm to locate the aircraft spatially with respect to the terrain. The terrain database around the aircraft is scanned, and a terrain profile is created. An aircraft response model is used to continuously predict the aircraft's future recovery trajectory. A recovery is automatically performed whenever the trajectory penetrates a preset distance from the terrain profile. This architecture, used in a previous "demonstration" system, is being retained in the enhanced system described in this paper.

A comparison of the limited "demonstration" automatic ground collision avoidance system with the enhanced system will be discussed. An explanation of the software tools and the methods for developing the ground collision avoidance system algorithms will be given.

F-16 and JAS39 Aircraft

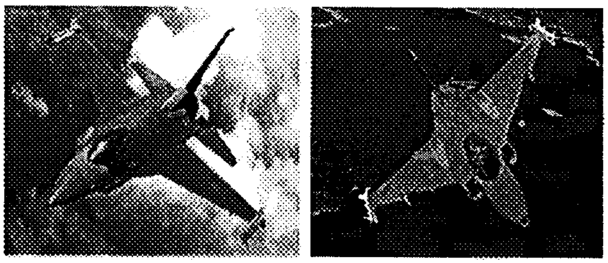

Figure 1.

Requirements based on simulation and flight test for an "operational" type of automatic ground collision avoidance system will be presented. A description of the design which allows transition to multiple aircraft will be explained. Flight test results of the automatic ground collision avoidance system will be discussed at the conference. The method utilized to eliminate nuisance flyups will be presented.

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This system was not intended to operate on large transport type aircraft; however, the design is applicable to both transports and commercial airlines. This paper will also discuss the necessary changes for large aircraft operation, as well as the safety implications of providing an automated recovery for these types of aircraft.

Introduction

Controlled flight into terrain due to spatial disorientation or lack of situation awareness has plagued aircraft pilots for many years. This condition has been compounded by the increase of information via cockpit sensors to the operator. Many kinds of ground collision warning systems have been developed over the years, and even though they provide a considerable warning capability, a large number of aircraft are still being lost due to controlled flight into terrain accidents. Part of the problem is due to a system design that forces the pilot to correct the situation. All of these designs contain a warning that must be given a second or two early in an attempt to account for the pilot's reaction time in recognizing the problem and correcting it. This reaction time, in many instances, causes the systems to issue a warning when the aircraft is not in danger. These early warnings are nuisances to the pilot and are either ignored or turned off. The only method to prevent nuisance warnings is to eliminate the pilot reaction time. In other words, the system has to be designed to always be in the background, allowing the pilot to maneuver to all attitudes and altitudes without causing a warning unless the aircraft is in danger of striking the ground.

The advent of digital fly-by-wire flight controls has allowed integration of various avionics systems with flight controls. The integration of avionics and flight controls to provide an automated means for aircraft recovery will prevent virtually all controlled flight into terrain mishaps. The system can be designed to react without a pilot reaction time, thus preventing nuisance warnings. An automatic system also has the added advantage of providing a recovery for G-induced loss of consciousness mishaps.

Ground Collision Avoidance Nuisance Criteria

An independent flight test program was established in 1996 to develop a nuisance criteria for ground collision avoidance systems that could be used to design a nuisance free system. In this effort, pilots determined the point, during maneuvering approaches to terrain obstacles, at which they would manually pull away from the terrain. For a collision avoidance system to be nuisance free, it must not interfere with normal maneuvering. Any automatic recovery must occur after the point at which the pilot would recover the aircraft.

The test data indicate that the pilot's opinion of where that point is can best be correlated with an apparent "time to ground impact" that includes the effects of airspeed, altitude, dive angle, as well as velocities and accelerations. Pilots demonstrated the ability to consistently recover the aircraft when the time to ground impact was between 2.0 to 2.7 seconds. A lower limit on this time to ground impact that includes all pilots tested would be approximately 1.5 seconds. This criteria is still being verified and refined. However, the results to date have altered the design of the enhanced system in a number of ways discussed below.

Demonstration versus Enhanced Design

A demonstration automatic ground collision avoidance system was developed and flight tested in the 1991-1997 time period on the AFTI/F-16 aircraft. At the time, technologies were being evaluated for low level night attack in a single seat fighter. The potential for momentary task overload and loss of situation awareness was extremely high. The consequences are aircraft and pilot loss due to controlled flight into the terrain. This demonstration system proved the viability of an automatic recovery to provide protection during low level close air support and battle air interdiction missions.

Due to time and money constraints, limitations were imposed on the system. The design was completed for one store loading. System operation was enabled for dive angles less than 60 degrees, altitudes less than 20,000 feet and airspeed between 250 knots and 0.95 Mach number. These were the expected conditions for the close air support and low level interdiction missions. The enhanced design removes these limitations. This new system provides protection at all attitudes, all airspeeds, all altitudes, in all mission phases with gear up, and for a large combination of store loadings.

Both designs share a common architecture as shown in Figure 2. The system continuously predicts the flight path of the aircraft, assuming a recovery is needed, 10 to 15 seconds in the future. This prediction is accomplished using a high-fidelity aircraft response model. At the same time, the terrain database around and in front of the aircraft's position is scanned to determine all terrain features that may be dangerous to the aircraft's flight. The scanned terrain points are collapsed onto a recovery profile and sorted by range into bins. The highest point in each bin determines the height of the bin. Bin width is selected based on navigation uncertainty. In the demonstration design, a line or hull was placed over these bins to create a simplified ground profile for computing the time-to-flyup. This hull was found to be too conservative in low angle approaches to terrain obstacles during nuisance criteria flight testing. In the enhanced design, the hull is not used. The terrain is represented by the tops of the bins. A comparison of the future recovery flight path and the terrain profile along the path (represented by bin tops) is made. From this comparison, a time-to-flyup is generated. At a time-to-flyup of 5 seconds, chevrons appear on the HUD as shown in Figure 3. When the time-to-flyup reaches zero, a coupler or auto-pilot in the flight control system commands an automatic recovery. The recovery is a roll-to-wings level, 5g pull up. If inverted at the flyup initiation, the system unloads the aircraft and counters gravity during the initial roll. The 5g pull is commanded as soon as the bank angle is less than 90 degrees. This recovery is continued until the projected flight path has cleared the terrain feature of concern. Changes to enable the system to provide expanded coverage were made to the scan pattern computations, the aircraft response model, the safety monitors, and the flight control couplers. Figure 4 illustrates the modification using two separate trajectory predictions to more precisely determine the time-to-flyup.

Automatic Ground Collision Avoidance Algorithm Architecture

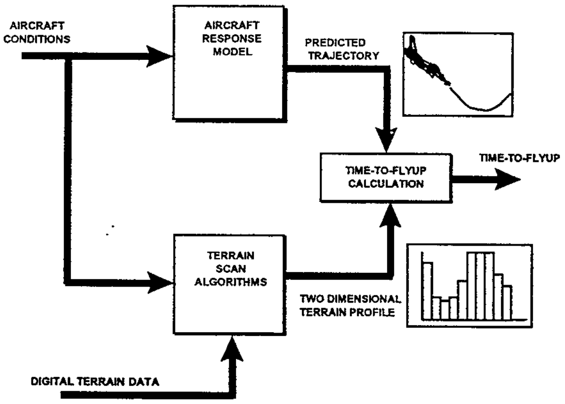


Figure 2.

Auto GCAS Display

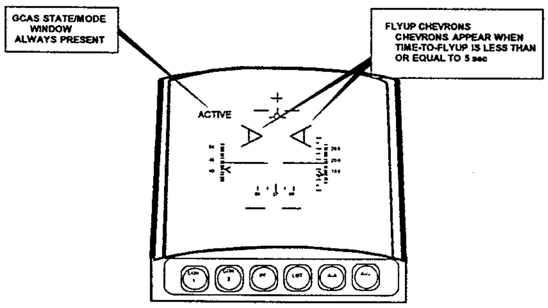


Figure 3.

Time-to-Flyup Calculation Two Trajectory Method

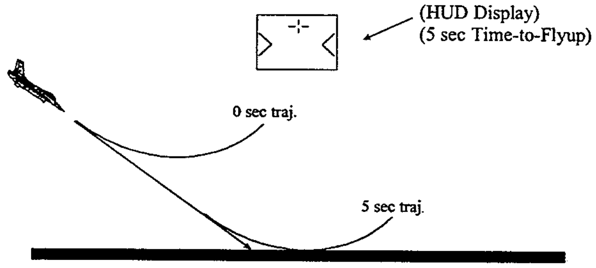


Figure 4.

Figures 5 shows the scan pattern variations for turning flight that were retained from the demonstration design. Changes made to the digital terrain scanning shapes in the enhanced design for inverted flight and steep dive angles are illustrated in Figure 6. The hexagon pattern is used to represent a circular scan shape.

Scan Pattern Variations with Turn Rate

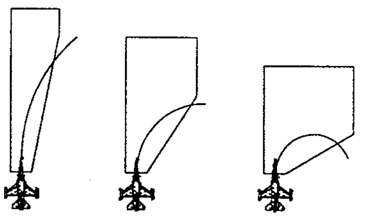
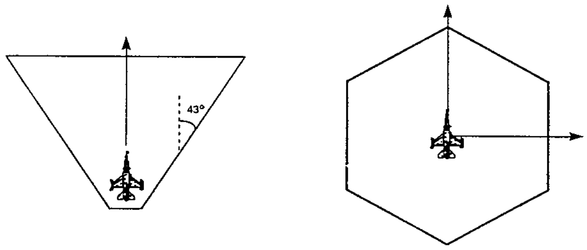


Figure 5.

The flight control coupler was altered to allow the control system to execute a recovery at slow speeds and while carrying a heavy store configuration. In the pitch axis, load limits for pitch command at low speed were added to Auto GCAS to allow for the full aircraft envelope and all store configurations. The final pitch command limits were increased on the positive side to allow for quicker onset rates. At the end of the recovery, the pitch rate is reduced to prevent the aircraft from coasting beyond the flyup termination angle. In the roll axis, damped proportional and integral feedback has been added to handle asymmetric loads. The roll rate limit was reduced to avoid ringing with heavy stores. Roll to wings level latching was added to improve the flyup performance.

New Scan Pattern Variations



INVERTED FLIGHT

HIGH DIVE ANGLES

Figure 6.

Pilot override of the system using a paddle switch on the stick will be retained. Thus, the pilot can always prevent an automatic recovery from occurring. In the demonstration system, the pilot could blend with the recovery by applying commands to the stick during the flyup. Flight test experience showed this could be dangerous. A stick command of a few milliseconds in opposition to a flyup resulted in the loss of several hundred feet in altitude during the recovery. Thus, for the enhanced design, pilot blending was modified to prevent stick commands until close to wings level during a flyup.

A significant difference for this enhanced design is the host hardware for the ground collision avoidance algorithms. This part of the system is being integrated into the hardware that holds the digital terrain system on the F-16. It is comprised of a cartridge and a cockpit receiving unit for the cartridge as shown in Figure 7. The cartridge is designated as a Mega Data Transfer Cartridge (Mega DTC), and the receiving unit is an Upgraded Data Transfer Unit (UDTU). The cartridge contains preplanned mission data along with the digital terrain database for the current mission, and a portion of the Auto GCAS algorithms. It is loaded at a mission planning station by the pilot and then carried to the aircraft as the mission begins. The UDTU contains the remaining Auto GCAS algorithms as described below.

Design

An off-line simulation known as Aircraft Trim, Linearization, And Simulation (ATLAS) is utilized to determine the most efficient recovery based on the aircraft flight condition and load. Numerous off-line simulation runs are then utilized to evaluate the accuracy of the aircraft response model. The aircraft response model is then tuned to match the ATLAS response. The optimum scan distance and pattern of the scanning algorithm are also determined by off-line simulation results.

Auto GCAS Software Rehost in Mega DTC & UDTU

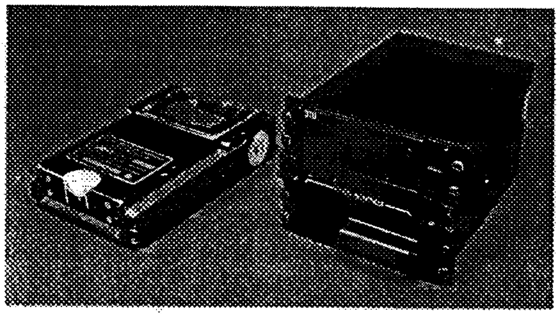


Figure 7.

The scan algorithm is evaluated by running flight data (or simulation data) and terrain data through the Video Cassette Recorder (VCR) tool. The VCR tool gives a frame-by-frame graphical description of the scan region, aircraft response model trajectory, two-dimensional terrain profile, and aircraft position during an actual recovery and allows comparison with the Auto GCAS design. Figure 8 shows a sample screen from the VCR tool. On the top right are aircraft responses during the flyup. Below this plot area is an overhead view of the scan pattern covering the discrete terrain points. The projected flight path and recovery path can be seen extending through the scan pattern. On the left is a side view of a recovery profile above the terrain. Digital and pictorial data of interest are presented above the profile. The ATLAS simulation of the coupler is written in FORTRAN and is run on a VAX computer. The aircraft response model is developed in C++ on a PC platform. The VCR tool is developed in C on a Silicon Graphics Unix platform. The design envelope includes all attitudes, and all airspeeds with gear up from minimum controllable to Mach 1.2 It also covers all Low Altitude Night Terrain Infrared Navigation (LANTIRN) store configurations up to a 25,000 ft-lbs asymmetry.

A safety function called System Wide Integrity Management (SWIM) was designed into the Auto GCAS specifically to provide a means to safely integrate flight control with other avionics. The SWIM function is like a built-in test for a system. It is a method to ensure that signals received from non-redundant portions of the Auto GCAS will not cause unsafe conditions. Most of the Auto GCAS is non-redundant with the exception of the flyup command which is in the quad redundant flight control computer. SWIM provides monitors that test and compare the signals from non-redundant systems utilizing the flight control system to accomplish these tasks. An example is aircraft attitude which is one of the most important parameters required for safe Auto GCAS operation. The attitude is compared with the integrated roll rate from the redundant flight control system. Should a failure of the aircraft attitude be detected during a recovery, the flight control system has enough information to complete the recovery.

VCR Analysis Tool Display

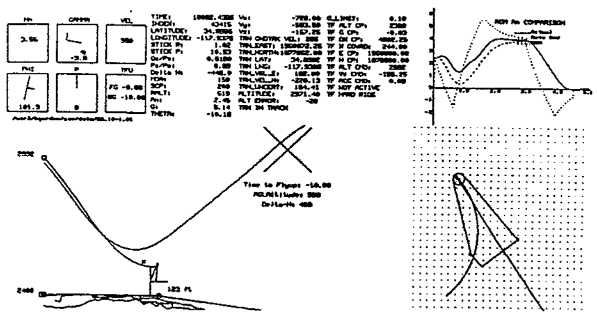


Figure 8.

Simulation Evaluation

Once the design is complete, the design requirements are submitted and implemented in the software resident in the allocated hardware. The recovery coupler software is hosted in the digital flight control computer hardware. The aircraft response model software is hosted in the Mega DTC hardware. The scanning algorithm software is hosted in the UDTU hardware. The allocation of the design with respect to hardware is shown in Figure 9. All simulation evaluation is performed in the F-16 hardware-in-the-loop handling qualities simulator. The design engineers evaluate the performance of the integrated system. Simulation is performed throughout the design envelope. The resulting simulation data can be retrieved and run through the VCR tool for evaluation of system performance. The VCR tool allows the engineers to localize the errors by comparing all the functions in one master graphical display. After evaluation, the pilots and flight test team perform their flight cards, request any necessary changes, and evaluate the system in general. The verification and validation group perform integrated tests as on previous F-16 releases and perform additional tests that are Auto GCAS peculiar. The verification and validation group also perform failure modes and effects testing. This testing includes failing different hardware systems and evaluating the response of the aircraft when these failures occur. The final process is to bring the pilots in again for the pilot confidence tests. The pilot confidence tests allow the pilots to again perform their flight cards and gain familiarity and confidence in the overall system. A representation of the test and evaluation process is shown in Figure 10.

Auto GCAS Design Allocation to Hardware

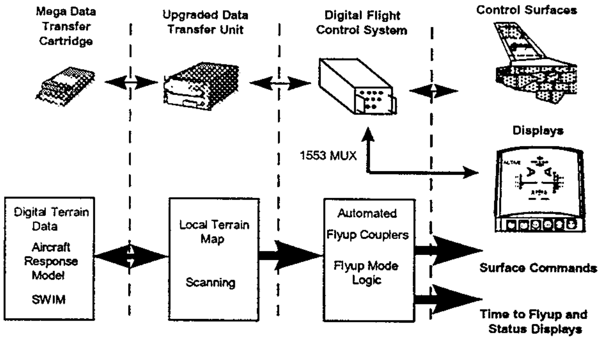


Figure 9.

Configuration Product Test and Evaluation Process

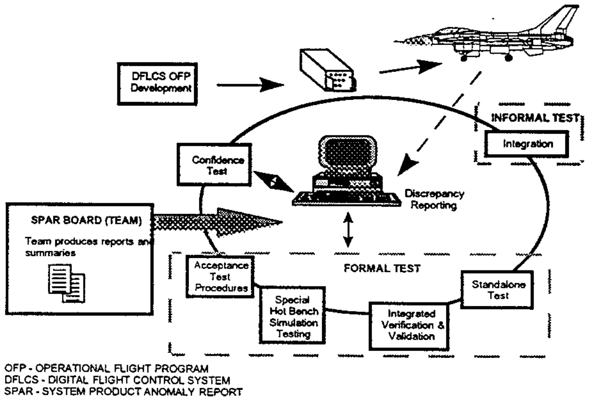


Figure 10.

Flight Test Demonstration Program

The flight test program began in May of this year. Testing was conducted using a two seat F-16 at Edwards Air Force Base in California. Pilots from the US and Sweden evaluated the system against a variety of terrain from flat Mojave desert dry lake beds to rugged Sierra Nevada mountains. Testing started at high altitude and worked downward to extreme low altitudes. Various dive angles and bank angles were tested, as well as several store configurations. The flight testing included flying representative operational mission phases to evaluate the system's acceptability during these missions. Testing was supported by a special mobile tracking and control center. All flights were conducted under real-time control from this mobile center. Both Swedish and US engineers participated in monitoring the flights and analyzing data. To show the ability of the system to prevent controlled flight into terrain, several accident profiles were recreated in-flight. In all cases the Auto GCAS protected the aircraft. Flight test results will be presented at the ICAS conference.

Transition Process

The design was partitioned to fit in any aircraft. The Auto GCAS is transitioned into another host aircraft by substituting new aircraft characteristics into the coupler, aircraft response model, and scanning algorithms. A different terrain database can be substituted as well. The primary objective on the host aircraft is the same -- to save the pilot/aircraft but not annoy the pilot with nuisance recovery warnings. The VCR tool evaluates the accuracy of all the elements and allows the designers to isolate anomalies to specific elements in the design. For the joint US/Sweden Auto GCAS program, a reduced version of the VCR tool has already been released to Sweden. The version sent to Sweden does not contain the F-16 specific flight data, terrain data, or aircraft response model. For the transition to Sweden's aircraft (Gripen) to be smooth, these pieces need to be integrated by engineers that are familiar with the flying and mission requirements of the Gripen. Specific flight data, terrain data, and aircraft response model elements that satisfy the flying and mission requirements of the Gripen will need to be integrated with the VCR tool. A Swedish engineer participated in the design of the F-16 Auto GCAS for six months during the early development phases. He obtained a good understanding of how things fit together and became most familiar with the VCR tool and development of the scanning algorithm. Plans are to provide VCR tool documentation that will allow engineers to learn how to use the tool and to make the tool more user friendly. Based on the joint US/Swedish Auto GCAS program, it is apparent that the VCR tool could be packaged such that the software and accompanying documentation could be transferred to any aircraft requiring an Auto GCAS system. The coupler and aircraft response model are specific to the aircraft. However, the general methods of recovery performance and prediction can be utilized to transition the Auto GCAS system to any aircraft.

Alternate Design Issues

Experience from the current manual warning system in use with the Swedish Air Force shows that a ground collision avoidance system is a tradeoff between system safety and nuisance warnings to the pilot which may force the pilot to turn the system off. Given a proper amount of forewarning before the flyup, the system can be approximated as a manual system with automatic capabilities if the pilot is incapacitated or does not respond properly. Transferring the automatic ground collision avoidance system to another platform means accounting for different aircraft dynamics, as well as, new fundamental design issues and design assumptions due to different mission profiles. Several issues for future refinements or transfers to other platforms have been studied during the development phase.

Modern fighters are highly integrated multi-mission aircraft, and it is likely that pilots of the future may no longer be the highly trained mission specialists they used to be. They will have to adapt to several roles, even during one mission. The Swedish Air Force, on a daily basis, uses extreme low level operations for attack and surveillance missions. Therefore, the main driver for the Swedish automatic ground collision avoidance system applications is likely to be the problem of taking the system even lower than currently designed and still having a nuisance free and safe system. The current design is estimated to allow nuisance free operation as low as 150 ft over all types of terrain. It is desirable that the system operates effectively at considerably lower altitudes over Swedish terrain. Changing the system for extreme low altitude operations will mean refinements to the aircraft response model, the terrain scanning algorithm, and the flyup coupler.

Failure detection, performed throughout the whole system, must be tailored to the specific hardware and software. However the major portions of these elements will be similar to all systems. The navigation system will be treated as a "black-box" whose outputs of position and position errors will be used by the system. Since these outputs vary from system to system, Auto GCAS must compensate for these variations.

The navigation error is one of the most important parameters for accuracy of the system. All terrain surrounding the aircraft within a circle of a radius equal to the navigation error will be used in the comparison to the predicted aircraft trajectory. This effect is shown in Figure 11 where a terrain profile has been calculated for a typical hilly Swedish terrain using a database with 50 m spacing between the data points and assuming various navigation errors. Shown as well is a pilot flying at 100 ft above the ground at 390 knots (200m/sec) and who is restricted to +/- 0.5g. Of course, this effect is accentuated for more mountainous terrain. Knowledge of terrain features such as water, forests or open terrain may also help in decreasing the minimum altitude that can be obtained. The terrain types likely to be encountered also affect the performance of the terrain scan. Even though the system is to be safe all through the envelope, mission planning is important in order to prevent nuisance warnings. Low speed in rugged mountainous terrain is likely to give very long flyup distances which some pilots may regard as a nuisance.

Navigation Error Impact on Terrain Profile

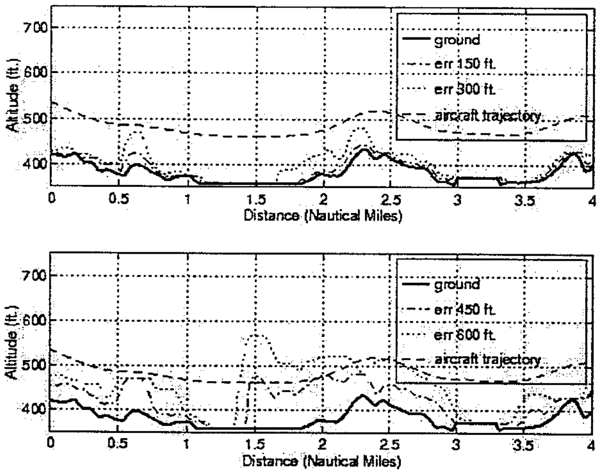


Figure 11.

The use of auto-throttle and airbrakes makes the flyup calculations more predictable and increases the accuracy of the system up to 5% of total altitude lost calculations. One problem with the auto-throttle is that it may be overpowered by a pilot experiencing G-induced loss of consciousness. This means that throttle position must be monitored and proper action taken if this occurs. In this case, one solution could be to make the coupler dynamic in the sense that it could be allowed to increase the maximum level of g's commanded for a recovery if critical inputs change dramatically. In order to take care of uncertainties in the aircraft response model calculation, one method could be to calculate flyup trajectories at one g-level and then increase the obtainable g's from the coupler by a small amount.

The aircraft response model is very accurate as currently designed in order to take care of a large envelope and a wide variety of loading configurations. Still some assumptions are made, and more exact methods regarding the aircraft dynamics could be used. The aircraft dynamics could be very demanding with respect to computational loads. For a less maneuverable aircraft, the response model could be simplified.

The scan area pattern was chosen to be simple but still cover all possible flyup directions in the calculated recovery trajectory and possible changes to the flight path made by the pilot during a calculation cycle. This means that the area is overly conservative for low level operations. Tailoring the scan area more to the maneuvers performed would be one possible solution. Smaller scan areas mean less computational loads. An alternative to the circular scan shape could be two triangular shapes, one in the forward sector and one in the backward sector, especially at pull-through where angular rates may have a greater effect on the time a pull-through is more efficient than a straight forward pull-up. In this case, one trajectory would be calculated for each sector and the most efficient one with respect to the terrain would be locked into the coupler. Suggestions of controlling the course during flyup have been discussed as well. The current method of deriving the scan area has few limits as to how complicated the area can be made. However, complexity affects system safety issues since the system gets more difficult to verify and validate.

Applicability to Large Aircraft

The Auto GCAS design can be integrated into large aircraft. The target aircraft would require a digital flight control system and preferably be fly-by-wire. An aircraft model of the specific aircraft would be integrated into the GCAS algorithm. The model would provide the necessary parameters to predict a future aircraft trajectory. The digital terrain scanning would be modified to allow for the slower response of a larger aircraft. In addition, the digital terrain elevation data would need to include all manmade obstructions in close proximity to airports.

It is believed that airlines have been reluctant to use automated systems due to the perception of higher risks. The perceived higher risk is that an automated system may be activated when not necessary and possibly cause an unsafe condition. Automated systems are also perceived to use more advanced technology than do manual systems. Advanced technology does not equate to higher risk. Automated GCAS requires that some systems be integrated with the flight control system. This can be thought of as impacting safety of flight.

While it is possible that an automated system can activate when not necessary, it does not correlate that this would be unsafe. The pilot always has the option to inhibit or override any automated maneuver. These nuisance conditions should be near zero if the system is designed properly. As explained earlier, an automatic GCAS has the advantage over a manual GCAS in that it does not have to compensate for the pilot's reaction time. This fact alone should eliminate most nuisance activation. There are still database errors that can cause nuisance cases. As the database gets more accurate over time, these also will be eliminated.

Another possible concern would be an inadvertent flyup in heavy traffic near airports causing airplanes to get too close. All of the above are possible reasons for apprehension to design automatic recovery into airliners. However, it is the belief of the authors, after the development of an Auto GCAS for the F-16, that this technology can be transitioned to large aircraft and result in a safe and nuisance free automatic system.

Conclusions

The Auto GCAS program described in this paper has been a success. From the viewpoint of all participants, the joint development process was valuable and a great success. The program reviews were considered informative, and a great deal of technical interchange took place. This process allowed for design improvements through the request for information from the contractor at the reviews. Technical interchange meetings were conducted at appropriate times in both Sweden and in the U.S. Participating in the F-16 design made it easier for Sweden to determine how they would integrate Auto GCAS into their aircraft. It gave the US valuable insights from a new design and different operational perspective. This was the intent of the joint program, and it appears that it proved to be a fact. The successful integration of Auto GCAS into Swedish aircraft will provide a great tribute to flight safety and perhaps show other aircraft manufacturers the impact of a well designed ground collision avoidance system.

The flight test results from this program show the benefits of an automated system. It shows that nuisance warnings are almost zero and that interference to the pilot is basically non-existent. Pilot acceptance of automated systems has been a problem in the past. This reluctance was based on insufficient knowledge of automated system operation or experience with inadequate manual systems. Future aircraft will be more complex both in pilot work load and in display technology. These facts alone will make the need for more automation imperative. It is not the intent of this program to provide data to help eliminate the pilot, but it is the intent to assist the pilot, so that he/she can accomplish the mission safely and effectively.

This is the first automated GCAS design. We hope that our success will be followed by many other designers. As a result, it will be much safer to fly in aircraft of all kinds in the future. This in effect will be our legacy.