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AUTONOMOUS COLLISION AVOIDANCE FOR AIR-TO-AIR OPERATIONS

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14. ABSTRACT

The use of Unmanned Air Vehicles (UAVs) over the past several years has become an important concept for military operations. Currently, multiple UAV flights are not performed due to the difficulty in the control algorithms and the lack of redundancy to handle failures. This paper describes the program for a safety system that prevents air-to-air collisions.

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Abstract

The use of Unmanned Air Vehicles (UAVs) over the past several years has become an important concept for military operations. Currently, multiple UAV flights are not performed due to the difficulty in the control algorithms and the lack of redundancy to handle failures. Control algorithm designs can be achieved to provide for multiple UAV operations but single thread system failures remains a problem. Also, unforeseen circumstances such as ground controllers flying the wrong course can cause air vehicles to arrive in the same airspace at the same time, which can cause a collision. Even in the case of autonomous UAV operation, flight management errors could result in time of arrival errors and air vehicle collisions. As more of these systems are utilized, the methods to control them become even more difficult and the possibility of something going wrong increases. There is also a desire to enable UAV flights within commercial airspace. This desire cannot be achieved until a proven method to prevent air-to-air collisions is implemented.

The design of an Automatic Air Collision Avoidance System (Auto ACAS) is intended to prevent air-to-air collisions between air vehicles. The Auto ACAS is not intended to replace existing designs such as the Traffic Alert and Collision Avoidance System (TCAS) but is intended to accomplish a recovery at the last instant to prevent a collision. TCAS and other systems in use today provide situational awareness and traffic advisories to enable pilots to perform de-confliction and manual avoidance maneuver and remain several miles apart. In contrast, Auto ACAS assumes such de-confliction and manual avoidance attempts have not succeeded and operates in a time span that does not allow for manual pilot reactions, thus it must be highly integrated and automated in operation. An automated TCAS could be used to keep apart UAVs and commercial airliners but this kind of design may be difficult to implement due to the fact that it was initially designed to instruct the pilot to make course changes and not automatically take control of the aircraft.

Automatic collision avoidance is necessary if Unmanned Aerial Vehicles (UAVs) are to "blacken the sky" in massed attacks, accompany manned fighters on combat missions, and transition civil airspace. These vehicles will, in some manner, have to "see and avoid" other aircraft. An automated air collision avoidance system will fulfill a part of this need. It will automatically maneuver an aircraft, at the last instant, to avoid an air-to-air collision. It will function in a manner similar to a pilot avoiding a

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collision. It is a system that must be reliable, verifiable, and partially redundant, forming the last line of defense against collisions. It must provide nuisance free operation and allow safe interoperability. The requirements for such a system will be discussed in detail. Of particular interest are criteria to enable a safe, nuisance free system that will have embedded rules of the road for all encounters. Autonomous control of unmanned aerial vehicles is a goal for the U.S. Air Force in the future. However, flying multiple unmanned vehicles in the same tactical airspace with manned fighters presents very challenging problems. Automatic collision avoidance is a necessary step in moving toward this goal.

Introduction

Tomorrow's Air Force will use Unmanned Air Vehicles (UAV) for a number of missions. High risk missions in which pilot loss is unacceptable are ideal candidates for such vehicles. Swarming large numbers of UAVs to saturate enemy defenses and bring overwhelming force to a conflict for extended periods of time is another possibility. Whatever missions are chosen for these vehicles, their numbers and use will significantly increase in the future. A way must be found to allow safe operation with manned aircraft in the same airspace. Collision prevention is also required when close flight with other aircraft is necessary for formation, refueling, and combat training.

To allow greater autonomy of operation, the onboard software programs for unmanned vehicles are growing at a high rate. On manned fighters, a large amount of software is considered mission critical since the pilot can intervene in the event of a program error. However, on unmanned vehicles this software and all of the programs that emulate the pilot's decision process are safety-of-flight critical. The ability to validate and verify this software is an ever-increasing problem.

The Auto ACAS program began in the year 2000, when officials at the U.S. Air Force Safety Center (AF/SE) at Kirtland AFB, N.M asked AFRL to design and implement an Automatic Air Collision Avoidance System for manned fighters. The U.S. and the Kingdom of Sweden had entered into a Project Agreement (PA) under a Technology Research and Development Program (TRDP) for the Automatic Ground Collision Avoidance System (GCAS) program several years ago. Sweden had been interested in preventing air-to-air mishaps also, so they again approved of a second PA under the TRDP for the Auto ACAS program. The Boeing Company, Lockheed Martin Aeronautics, and Saab AB were contracted to conduct a concept study from May 2000 to March 2001. The concept study results indicated that it was feasible to design an Auto ACAS.

Why Automatic

The definition of a manual system is one that produces a warning to the pilot to take an action. These warnings can be in the form of aural, visual, or both. The timing of these warnings is the basic issue as to why an automatic system is superior. The timing depends on the specific pilot and how he/she perceives a warning. A warning too soon can be perceived as a nuisance for some pilots and too late a warning may not give the pilot enough time to react. The balance on timing can never be designed correctly do to the fact that everyone has different perceptions and capabilities. Many studies have been conducted both in simulation and in flight to try to obtain a correct design. The mishaps have continued to vary over the years but never have been zero.

In contrast, an automatic system does not depend on pilot reaction. The system makes the decision to react and can be adjusted to react at the last instant so that the perception of nuisance is virtually eliminated.

The automatic design does not completely eliminate the nuisance factor. In fact it becomes more important. The pilot/operator must be satisfied that the automatic maneuver activates at the proper time and accomplishes the correct maneuver. If an automatic maneuver activates too soon, the pilot/operator will have the perception that he/she could have performed the maneuver and not need the automatic system. Of course if it activates too late the result would be catastrophic. A too early activation will also create the nuisance factor. It needs to activate after the pilot/operation would normally activate the same escape maneuver.

There are reasons why automatic systems have been avoided in the aerospace industry. The most apparent reason is the fact that no pilot/operator is content to give up control of his/her air vehicle to a computer. Another important reason is that to accomplish the automatic function, flight control must interface with various avionic subsystems. This has been fought within the aerospace industry. Flight control, due to its importance in the air vehicles survivability, must have several orders of magnitude greater loss of function than other avionics subsystems. Redundancy is applied to flight control systems to achieve this greater protection against loss of function. It has been thought that if redundant systems were to interface with single thread systems, the result would be that the single thread system characteristics would become dominant. This thinking has led to the many manual collision avoidance systems within the aerospace industry today.

Another issue that caused manual dominance was cost. A manual system only needs to implement avionics subsystems that are currently on the aircraft. Displays are available to allow added functions to give cautions and warnings to the pilot. The design of an automatic system must include the flight control system. More testing is required which drives the cost.

There is one technology that has implemented automatic operation and that is in Terrain Following (TF). It is not clear exactly why this technology has utilized the automatic concept except that it is highly demanding to manually fly an aircraft at low altitudes over rolling terrain. However, even in the case of TF, the systems always had a manual mode.

System Requirements

Based on the concepts and discussions above, a set of system requirements can be established for an automated air collision avoidance system:

1) The system must provide a last resort emergency automatic maneuver to prevent collisions with other air vehicles. This requirement is necessary to prevent nuisance activation.

2) The system will not interfere with normal vehicle control except to prevent aircraft loss. It is to be nuisance free.

3) The system is to provide a predictable response operating as the pilot would to avoid a collision.

4) The automatic escape maneuver will be commanded only long enough to avoid the collision. Termination criteria will be established.

5) The system is to protect against unforeseen events that cause collisions.
6) The system can be relied upon to insure safe vehicle operation. It will be fully verified, validated, and tested with redundant elements as required.

7) The system will make extensive use of distributed integrity monitoring to insure fail-safe operation without the use of brute force redundancy.

8) The system will be designed to operate with GPS or data link loss.

Time-To-Escape

Air Traffic advisories and warnings, flight path de-confliction, and aircraft collision avoidance seem to imply similar requirements for a vehicle. In this paper these actions are shown to be quite different and easily separated by their time of action.

Collision avoidance is concerned with the last minute emergency maneuver to prevent aircraft loss. It is not concerned with traffic advisories/warnings or de-confliction. One good way to separate these functions is to consider the time, prior to a potential collision, during which the systems are expected to operate.

The aircraft maneuvering to avoid a collision requires a finite time to obtain separation distance. Thus, a point in time can be defined, along the predicted trajectory of one aircraft, for the initiation of a defined "escape maneuver" that will just touch the other aircraft. Maneuvering at or beyond this point will not prevent the collision. This point is defined as the zero seconds time-to-escape initiation point since there is no time left to prevent the collision due to the physical maneuver constraints of the avoiding aircraft. Moving back in time from this point along the predicted trajectory yields the time available to escape a collision.

This concept of time-to-escape comes from the flight testing of an automatic ground collision avoidance system by the US Air Force at Edwards AFB in California. To illustrate the concept, consider two vehicles on a collision path as shown in Figure 1. The vehicle on the left is to initiate an automatic escape maneuver. Since the vehicles are within a "tracking zone," their trajectories are being predicted and the vehicle on the left determines the collision point. The collision avoidance system is designed to fly a path that will remain clear of the other aircraft.

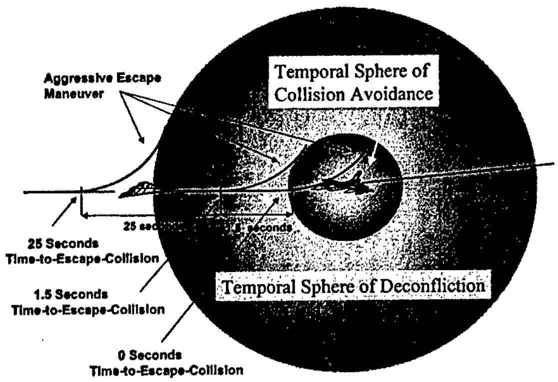

Figure 1. Time Separation of Functions

The maneuver is moved along the aircraft's future trajectory by advancing its initiation point. Beyond this point, the escape maneuver cannot prevent collision. The point at which a pilot would initiate a last-minute escape maneuver is then established. In this example, a point 1.5 seconds prior to the zero seconds time-to-escape maneuver point is selected.

The recovery trajectory defines the temporal sphere of collision avoidance. An automatic collision avoidance system must initiate between these points, maneuvering within the collision avoidance sphere, if it is not to interfere with the pilot and provide the desired protection. The distance at which the system must initiate an escape maneuver changes with each encounter geometry. However, the time over which it must react remains constant. Thus it is easier to visualize system operation by considering temporal spheres whose radii are measured in time.

In an actual system an exclusion zone consisting of a physical distance around the target vehicle will be pre-established. The system will prevent penetration of the exclusion zone. The tracking zone in which neighboring aircraft are observed is centered on the vehicle with the automatic collision avoidance system. The collision avoidance and deconfliction spheres are projected onto the neighboring aircraft that pose a collision threat. Although useful for visualization, in practice a sphere is not calculated. The initiation point on the sphere is calculated. The sphere is the solution of all potential collisions with the vehicle from all aspects. We are interested in only one solution at any time.

By using this time-to-escape parameter, we can separate the areas of interest for traffic advisories, conflict resolution, and collision prevention. UAV deconfliction operates in the 25 seconds time-to-escape range. Note that deconfliction is concerned with attempting to resolve potential collisions at a range that allows the mission to continue without major replaning. Traffic warnings and advisories for TCAS occur at in a 25 to 45 seconds time-to-escape zone. Collision avoidance assumes that TCAS advisories and autonomous deconfliction have failed to resolve the problem.

Integration Safety

Flight control systems are designed with redundancy to achieve the required loss of control parameter. Systems are usually triplex or quad redundant in order to achieve this parameter. In a quad system, a first failure is voted off and the system continues to operate as a triplex system. A second like failure will again be voted off and the system continues to operate as a dual system. These systems are called two fail operate.

If a single thread avionics subsystem is integrated into the flight control system, one method of failure detection is to create a similar function utilizing redundant subsystems. An example that has been employed is to utilize the quad flight control gyros to give a short time calculation for an Inertial Navigation System (INS). The INS is utilized in many automatic maneuvers to provide information that holds the aircraft in a certain position during an automatic maneuver. Example: Suppose the INS has a hard over failure. Each of the quad digital flight control system computers monitors the INS and when the failure is detected, the flight control gyros can provide data for the flight control computer to compute the INS function for a short time period. The time required is normally very short due to the short duration of the automatic maneuver.

There are other types of methods to ensure safe avionics integration such as sending a calculation for an avionics computer to accomplish. Designing a coded message that the avionics computer sends at a specific periodic rate is also a method employed.

Data Link versus Sensor Operation

In the early discussions on program plans, both sensors and data links were considered for the design of the Auto ACAS. Surveys were conducted to determine availability and whether specific technologies could meet the Auto ACAS requirements. One of the driving points for making the decision was that whatever technology was chosen, it required to be integrated onto an aircraft and flight tested. It was determined that integrating a data link was less costly than a sensor. This was of course only for a new sensor. The existing radar on the aircraft could be utilized. Due to the cost, the decision was made to use a data link.

Algorithm Development

The algorithm development began early in the program. It was initially integrated into an off line desktop simulator called D-Six. The D-Six simulator has been a valuable tool to test the algorithm in the early stages of development. It has also been used along with the real time simulation testing.
The algorithm interface design was frozen early in the program so that the integration for the F-16 could progress without interface changes. This process allowed the algorithm to go through several releases that improved performance.
The algorithm utilizes a claim space method to predict where the aircraft will be at a given time. Figure 2 shows the escape maneuvers. The cones produced are a result of uncertainties due to navigation errors.
The size of the claimed space is computed using knowledge of the wingspan, navigation uncertainty and accuracy of the predicted trajectory compared to the one the automatic digital flight control system (DFLCS) will make the aircraft follow if the escape command is given.
Each aircraft sends its predicted escape maneuver and the size of the claimed space along this track to the other aircraft, using the data link.

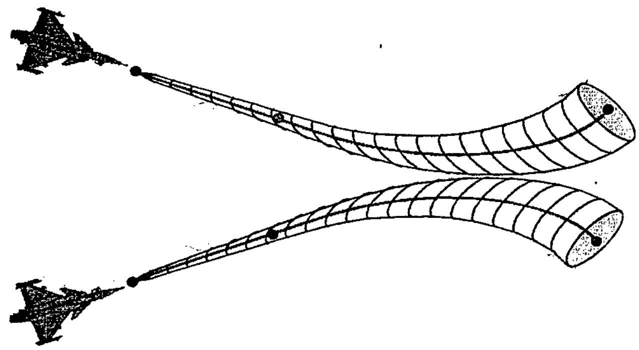

Fig. 2. Collision detection using predicted escape maneuvers

Escape Maneuvers

The Auto ACAS algorithm has two basic escape maneuvers. One is to pull 5 g's for piloted tactical aircraft, and to pull the maximum g available for Unmanned Air Vehicle (UAV). The other is to roll at the roll rate of 60 degrees per second for piloted tactical aircraft, and to roll at the maximum roll rate for UAV; followed by pull as in the first escape maneuver. Calculating the amount of angle needed to roll the wings parallel to the collision plane generates the roll command.
To meet the nuisance criteria, the algorithm was designed to initiate the execution of the selected escape maneuver at the last moment before the collision becomes inevitable, and to terminate the escape maneuver as soon as the minimum separation distance is reached. Thus it performs the collision avoidance with minimum interference to the pilot.

Flight Test

One of the test aircraft chosen for the flight test was the Variable Stability In Flight Simulator Test Aircraft or VISTA/F-16. The reason for VISTA was to be able to simulate a UAV. The Auto ACAS algorithm will be integrated into the Variable Stability System (VSS) computer on VISTA. The VSS is a computer that provides the simulation capability for VISTA. For the Auto ACAS program, VISTA would have two purposes, to simulate an F-16 and to simulate a UAV. The second aircraft for the flight test is an F-16.
The flight test was divided into four sessions to provide data link tests and an early look at the algorithm. The sessions are listed below.

Session I
Data link transmissions between VISTA and the D-Six ground station. VISTA with a virtual target controlled by the ground station.

Session II
VISTA configured as an UAV and flown with a virtual target.

Session III
First flight of F-16 flown with a virtual target.

Session IV
VISTA flown with the F-16. VISTA configured as an F-16 and as an UAV.

Conclusions

The flight operation of the Auto ACAS will show that an algorithm can be utilized to safely maneuver a manned air vehicle automatically and not interfere with normal pilot operations. It will only be required to function for very short time periods and only to prevent a potentially fatal mishap.

Safe operation of UAVs and manned aircraft in the same airspace can be ensured by an automated collision avoidance system as discussed in this paper. It will be used to prevent UAVs from hitting other aircraft flying in the vicinity. It will also provide the capability for UAVs to fly close together and prevent collisions. The Auto ACAS will be the first necessary step in providing the capability to allow swarming of hundreds or thousands of UAVs.

Position uncertainty and data latency can significantly impact a system's operation. Both can cause an escape maneuver initiation sooner than desired. At some point, these effects will result in interference with the fighter pilot or the UAV operation. Further study of these effects and methods to accommodate the various requirements described are needed. These problems will arise for both a data link or sensor based system.

The system at the current stage of development indicates that it can provide the computational capabilities needed for a nuisance free design. Simulation results thus far have shown that the Auto ACAS has achieved nuisance free operation.

Flight testing the algorithm will be the final step to show an Auto ACAS design that will provide collision protection. The algorithm will be ready to transition to other platforms once the flight test is successfully completed.

The successful implementation of the Auto ACAS algorithm will be a tribute to the hard work and teamwork that the Auto ACAS program has accomplished. All of the organizations mentioned in this paper contributed to this success.