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INTEGRATION TECHNIQUES FOR PREVENTING COLLISIONS BETWEEN AIR VEHICLES

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The use of data links to control Unmanned Air Vehicles (UAVs) from ground controllers over the past several years has become an important concept for military operations. Currently, multiple UAV flights are not performed due to the possibility of air-to-air collisions. Control algorithm designs can be achieved to provide for multiple UAV operations, but unforeseen circumstances such as ground controllers flying the wrong course could cause air vehicles to arrive in the same airspace at the same time, which could cause a collision.

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Abstract

The use of data links to control Unmanned Air Vehicles (UAVs) from ground controllers over the past several years has become an important concept for military operations. Currently, multiple UAV flights are not performed due to the possibility of air-to-air collisions. Control algorithm designs can be achieved to provide for multiple UAV operations, but unforeseen circumstances such as ground controllers flying the wrong course could cause air vehicles to arrive in the same airspace at the same time, which could 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.

This paper will discuss the integration of data links in the design of an Automatic Air Collision Avoidance System (Auto ACAS) for aircraft, which is intended to prevent air-to-air collisions between air vehicles. This system is not intended to replace existing designs such as the Traffic Alert and Collision Avoidance System (TCAS) but 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 maneuvers 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 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 as 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 US 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.

This paper also discusses the planned integration of sensors into the Auto ACAS algorithm to provide complete "see and avoid" technology for the UAV. Planned use of both active and passive sensors will allow operation in and out of weather conditions.

Introduction

Tomorrow's Air Force will use unmanned air vehicles for a number of missions. High-risk missions in which pilot loss is unacceptable are ideal candidates for such vehicles. Swarming large numbers of vehicles 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. We must find ways to allow safe operation with manned aircraft in the same airspace. Although collision is to be prevented, 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.

One solution to insure safety is to create a separate entity within each UAV to provide some of the basic "see and avoid" capability of manned aircraft. Such an entity would be easily verified and validated. It would automatically maneuver the air vehicle, at the last instant, to avoid collision with another vehicle. It would allow safe operation of multiple UAVs and manned aircraft in close proximity. Portions of these systems would have redundant elements to provide the necessary level of safety.

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.

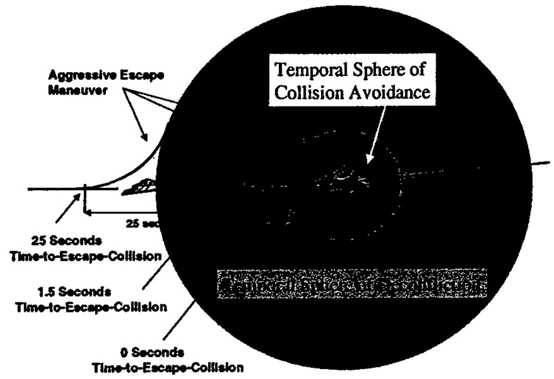

Figure 1. Time Separation of Functions

An aggressive escape maneuver is defined. The maneuver is moved along the aircraft's future trajectory by advancing its initiation point. The initiation point of the maneuver that just touches the other aircraft is defined as the zero seconds time-to-escape 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.

Basic 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. The expected operation is between 0.5 - 1.5 seconds time-to-escape.

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) It 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 work with GPS or data link loss.

9) UAVs will always execute an avoidance maneuver before manned aircraft.

10) The system will be designed to operate in both manned and unmanned air vehicles.

11) The system is designed to prevent air-to-air mishaps as well as allow a mix of UAVs and manned aircraft to fly in the same air space.

12) The system will be designed to be modular and transportable to multiple aircraft including commercial applications.

Automatic versus manual maneuvers

There are no automatic collision avoidance systems currently being applied within the aerospace community. This fact appears to be alarming due to the vast technology available to this industry. Yet it has been fought fiercely for various reasons. 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 also 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. While it is true that allowing a single thread command to a redundant flight control computer in itself appears to be a dangerous event, there are methods to achieve a safe automatic maneuver.
Before these methods are discussed it seems reasonable to explain why it is important to even consider the design of an automatic system. Manual systems have been in place for many years so why should this drastic step be taken to design automatic operation. First, the basic philosophy of a manual system is that the pilot/operator will accomplish the required function within the required time. There are two operations that need to be performed, the required function plus doing it in time. To make it simple, the time can be extended to give the pilot/operator time to determine what function to accomplish. Extending the time also extends the distance between the air vehicles making things like formation, refueling, and air combat training, and UAV swarming impossible for a manual system. As the time is decreased, the decision to choose the correct manual operation increases the workload on the pilot/operator.

Another problem of manual systems is the nuisance factor. A definition of a nuisance is a warning that occurs when it is perceived not required. An example might be an altitude warning where the pilot/operator gets an aural or visual warning and his perception is that everything is proper. Time marches on and the warning continues, the warning is ignored, and the aircraft hits the ground or another aircraft killing the pilot and destroying the aircraft. An automatic system solves this problem immediately since the control function is removed from the pilot/operator and the computer performs the required function.

The automatic design does not eliminate the nuisance factor. In fact it becomes more important. The pilot/operator must be satisfied that the automatic maneuver activated at the proper time and accomplished 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.

Safety Methods for Flight Control/Avionics Integration

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 compute the INS function for a short time period. The time required is normally very short due to the short time 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 and ensuring the correct answer. Designing a coded message that the avionics computer sends at a specific periodic rate is also a method employed.

Sensor Operation

The choice of a data link for the Auto ACAS flight test was one of availability and cost, not performance. For data link operation, each air vehicle must have the capability to link flight parameters to each of the other air vehicles. This in-network process can function quite well in relatively small groups of vehicles but if the need arises to provide collision prevention between large groups or swarms of air vehicles, the system breaks down.

There are of course other types of sensors that do not need exact compatibility between air vehicles. Active sensors such as radars or lasers can function quite well to provide information to the host vehicle to prevent collisions. These types of sensors do not depend on exact information exchange that is required by data link operation. The host vehicle can maneuver within any number of other platforms without colliding. Each host vehicle does not need to have identical sensors on board to accomplish the collision prevention function. These kinds of sensors can provide protection from out-of-network aircraft or aircraft that have no data link or sensor on board.

Automatic Air Collision Avoidance (Auto ACAS) Algorithm Development

The Auto-ACAS algorithm does not try to identify collisions based on predicted probable trajectories of the aircraft. Instead it claims space along a predicted escape trajectory (time tagged positions were the aircraft will be after an avoidance is executed) which the aircraft will use in the case an avoidance

maneuver is necessary. The major benefit of using an escape trajectory is that it can be predicted much more accurate than the probable trajectory which the aircraft will follow if no avoidance is executed. This is because the escape trajectory is executed automatically in a predetermined way by the Auto-ACAS algorithm, whereas the probable trajectory is affected by the change in pilot commands. 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. All aircraft will use the escape maneuvers from the different aircraft to detect a future lack of escape, see Fig. 2. If the distance between the escape trajectories is greater than the safety distance, the track is stored as the one to use in case of avoidance. Else the avoidance is executed using the DFLCS to make the aircraft follow the stored trajectory.

The escape maneuver directions are chosen to maximize the minimum distance between all aircraft. In this way the avoidance will be executed at the last possible instant and the system will thus guarantee a very low nuisance level.

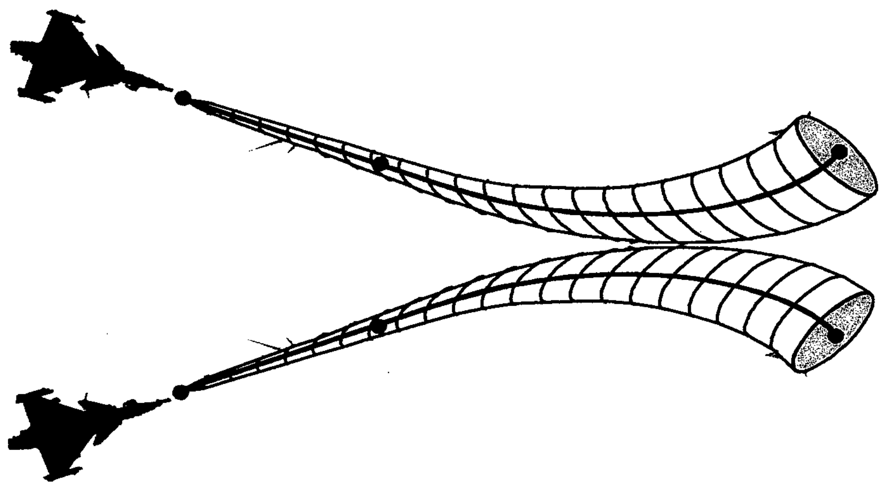

Fig. 2. Collision detection using predicted escape maneuvers

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. To determine the escape maneuver initiation time that reflects this philosophy, the sphere of safety zone is put around the host aircraft, and the two basic escape maneuvers are flown by the FOM to project the respective flight path. At the moment when both escape maneuvers can no longer keep the intruder aircraft out of the sphere of safety zone, the escape maneuver is executed.

Conclusions

The design of the Auto ACAS will show that an algorithm can be developed 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. It will also provide the capability for UAVs to fly close together and prevent collisions. This will be the first necessary step in providing the capability to allow swarming of hundreds or thousands of UAVs. This program is currently in its early stage but much has been learned about the approach in obtaining a suitable design.

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 regardless of failures it may have sustained. The approach described can be used to develop a system for both manned fighters and UAVs. Such a system will provide protection that initiates at the last instant before a collision and does not interfere with normal operations of either vehicle.

Position uncertainty and data latency can significantly impact such 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.

Initial engineering assessments have concluded that a system using current data links could provide a nuisance free design within the time-to-escape criteria. A system meeting the requirements presented is within the realm of the possible, although additional studies and analyses are needed to quantify the actual data rates and computational capabilities needed.