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AUTOMATIC AIR COLLISION AVOIDANCE SYSTEM

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This paper presents an algorithm for an Automatic Air Collision Avoidance System under development by the U.S. Air Force and its Swedish counterpart, Forsvaret Materielverk (FMV). The algorithm uses optimal coordinated escape maneuvers to avoid mid-air collision, while satisfying the imposed system requirements. In addition, the algorithm can simultaneously accommodate multiple aircraft in a collision course by activating the coordinated escape maneuvers. On the other hand, the algorithm has logic to allow close formation flight and rejoin without activating the escape maneuver. The algorithm is designed to operate safely against failure and GPS/data link dropout.

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Automatic Air Collision Avoidance System

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Abstract: This paper presents an algorithm for an Automatic Air Collision Avoidance System under development by the U.S. Air Force and its Swedish counter part, Forsvaret Materielverk (FMV). The algorithm uses optimal coordinated escape maneuvers to avoid mid-air collision, while satisfying the imposed system requirements. In addition, the algorithm can simultaneously accommodate multiple aircraft in a collision course by activating the coordinated escape maneuvers. On the other hand, the algorithm has logic to allow close formation flight and rejoin without activating the escape maneuver. The algorithm is designed to operate safely against failure and GPS / data link dropout.

Keywords: Air Collision Avoidance, Automatic System, Coordinated Escape Maneuver, Nuisance Free, Failure Safe

Introduction: The United States Air Force (USAF) Safety Center has reported that mid-air collisions are the leading cause of fighter aircraft losses. Mid-air collisions pose a threat to aviation safety whether it is air-to-air combat training or a formation rejoin mission. The Swedish AF recently had an incident where the flight lead was almost hit by his wingman during air-to-air combat training. Tomorrow's USAF will use uninhabited air vehicles (UAVs) for a number of missions. High-risk missions are ideal candidates for these vehicles. However, for them to realize their full potential and become an integral part of USAF airspace operations, they must be safe to operate in the same airspace with manned aircraft. For manned aircraft, several air collision avoidance systems are in use that alert pilots to potential collisions at distances of several miles. All of these systems require pilot action to avoid the collision. These manual collision avoidance systems often create nuisance events that interfere with the pilot's ability to perform the mission. Pilots quickly become tired of nuisance alerts and turn the systems off.

Currently, the United State Air Force Research Laboratory, The Boeing Company, Lockheed Martin, FMV, and Saab are jointly developing the Automatic Air Collision Avoidance System (Auto ACAS). The program is divided into two phases; a conceptual study phase (phase 1), and a system design and flight test phase (phase 2). Boeing, Saab and Lockheed Martin completed phase 1 in May, 2001. During this phase, Saab and Boeing developed two different algorithms. The architecture of the Boeing algorithm was presented in Reference 1. The system design and flight test phase started in August 2001 and will be completed in August 2003. Saab and Boeing are jointly developing a generic algorithm as a result of the study phase. Lockheed Martin will tailor the algorithm and integrate it into an F-16 for flight test in July 2003.

The following are the basic requirements for the Auto ACAS. The system will: 1) provide a last resort emergency maneuver to avoid collision with another air vehicle(s) – (It is expected to initiate an escape maneuver less than 1.5sec prior to the minimum time-to-evade), 2) provide a predictable response similar to the response a pilot would command in order to avoid a collision, 3) protect against the unforeseen events that cause collisions, 4) accommodate failure conditions with acceptable results, 5) not interfere with the pilot's tasks except to prevent aircraft loss, 6) work with GPS or data link loss, 7) be fully verified, validated, and tested with redundant elements to insure safe vehicle operation, 8) force a UAV to maneuver to avoid a collision with a manned aircraft before the manned vehicle must maneuver.

In what follows, the architecture of the Auto ACAS algorithm is first discussed. Then discussion on how the Auto ACAS algorithm is designed to meet the requirements follows. Simulation results showing the performance of the algorithm are also presented. Finally, the ACAS algorithm development status is summarized in the concluding remarks.

1. Algorithm Architecture

Figure 1 illustrates the architecture of the algorithm. The algorithm operates with three basic assumptions. First, because all aircraft maneuver to avoid collision, all aircraft must operate with data provided at the same absolute time. For data received over a data link, this means that the data latency must be considered, and dead-reckoning correction must be applied to bring all data to the same absolute time. Second, the computations in each aircraft processor must result in the same escape maneuver, so the algorithm in each aircraft must operate on the same data. Third, the escape angle computed by each aircraft must not be allowed to vary by a large amount as the time to perform the escape maneuver approaches, since the escape solution for all aircraft must be stable.

Initialization
For the first time through the algorithm, the first escape maneuver is initialized using the Accurate Aircraft Response Model (AARM) for a zero-bank escape, and two other escapes are computed at a preselected maximum spread angle using the Simplified Aircraft Response Model (SARM).

Data Link Data In
Brings in data for "In-Network" intruders.

Out-Network
Brings in data for "Out-Network" intruders such as radar, sensor, or third-party data.

Coarse Filter
Selects up to three intruders (aircraft other than your own) that should be considered the biggest threats to the host (your own aircraft). Selected aircraft are evaluated by the remainder of the algorithm.

Dead Reckon
Adjusts intruder and host data so that all aircraft (intruders and host) are evaluated at the same absolute time. Positions are corrected using constant velocities and known data latencies.

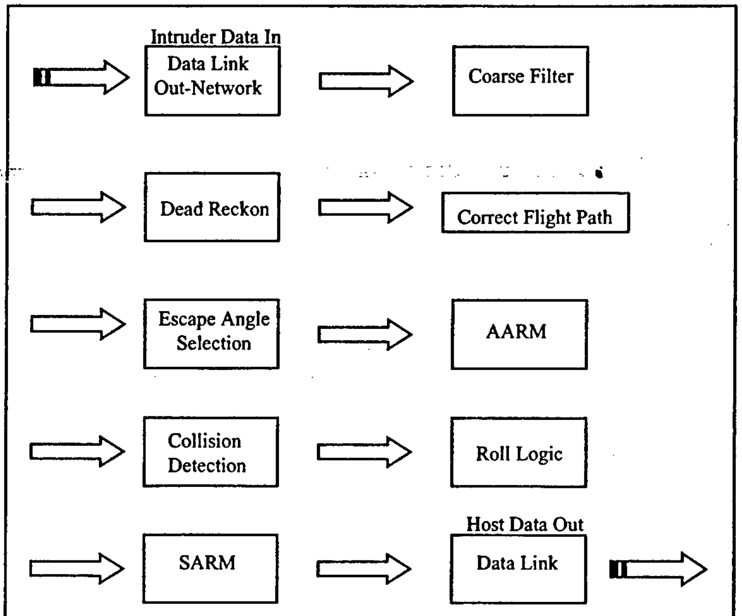


Figure 1 – Algorithm Architecture

Correct Flight Path
Corrects the flight path for intruders if two aircraft in a collision coarse differ in maneuverability. If a tanker and a fighter are on a collision coarse, for instance, then the fighter (more maneuverable than a tanker) maneuvers first to get out of the tanker's flight path. In this process, the tanker's flight path is corrected such that it flies straight along the current velocity vector. Flight correction is also made when the host is uninhabited and intruders are inhabited. Due to system requirement No. 8 discussed above, the inhabited aircraft flies a straight path along the current velocity vector and the uninhabited aircraft gets out of the way.

Escape Angle Selection
Compares all possible combinations of each intruder's three escape maneuvers (single straight-line flight for out-network intruders) with the host's three escape maneuvers. Escape maneuvers are provided by the projected aircraft position at 0, 3, and 6 seconds away from the current time using the fly out model. Escape maneuvers are compared along a quadratic fit to the three time points, and the minimum separation distance (MSD) and minimum separation time are computed. Computes the reciprocals of each MSD, and computes the sum of the reciprocals for each multiple-intruder case. Selects the preferred host escape maneuver that corresponds to the minimum of the reciprocal sums. Returns the angle of the preferred host escape maneuver as the Escape Angle.

AARM
Accurate Aircraft Response Model is a detailed model of the host aircraft. Degrees-of-freedom depend on accuracy desired. Calculates the Escape Maneuver along the Escape Angle provided using aircraft state information. Output is position at 0, 3, and 6 seconds, and velocity at 0 and 6 seconds.

Collision Detection
Computes the Minimum Safety Separation Distance (MSSD) based on host and intruder AARM data plus a radius of uncertainty in current and future positions. The time at minimum separation from Escape Angle Selection is used as a first approximation. The MSSD and time at MSSD are returned. If MSSD is zero, an escape maneuver command is sent to the host flight controls. If the host and closest intruder are converging, computes the time remaining to escape maneuver activation by dividing MSSD by closure speed.

Roll Logic
Determines how much the escape angle solution can vary from frame to frame by limiting the spread between the computed AARM and two SARMs. The logic compares data from older frames with the last frame to determine where to recenter the escape angle search for the current computational frame. The spread of the SARMs is increased if the solution is changing rapidly or decreased if the solution is stable. However, changes in the spread of the SARMs are limited to small amounts as the time until maneuver execution decreases in order to keep the overall solution stable for all aircraft.

SARM
Simplified Aircraft Response Model is a simplified 4-degree-of-freedom model of an aircraft with specific available g and available roll rate supplied by the host aircraft. Calculates the Escape Maneuver along the Escape Angles at the spread provided by Roll Logic. The model uses aircraft state information from the host. Output is position at 0, 3, and 6 seconds.

Data Link Data Out
Sends host data to "In-Network" intruders.

2. Algorithm Description

In the previous section, components that constitute the algorithm were described. In this section, the logic within the algorithm that enables air collision avoidance is described.

2.1 Optimal Coordinated Escape Angle

In order to select the best escape maneuver against multiple intruders, the algorithm first calculates the estimated minimum separation distance between the host and each intruder. This is done by curve fitting both the intruder and host flight path with quadratic curves as a function of time, and by finding the analytic solution for the minimum separation distance between two curves (see Figure 2 and 3 for a single intruder case). The quadratic curve fit uses three extracted position points (position at time 0, 3, and 6 seconds) from the host and intruder's 6 second long projected flight paths. The 6 second long flight paths for host and intruder are calculated by 4 degree-of-freedom equations of motion.

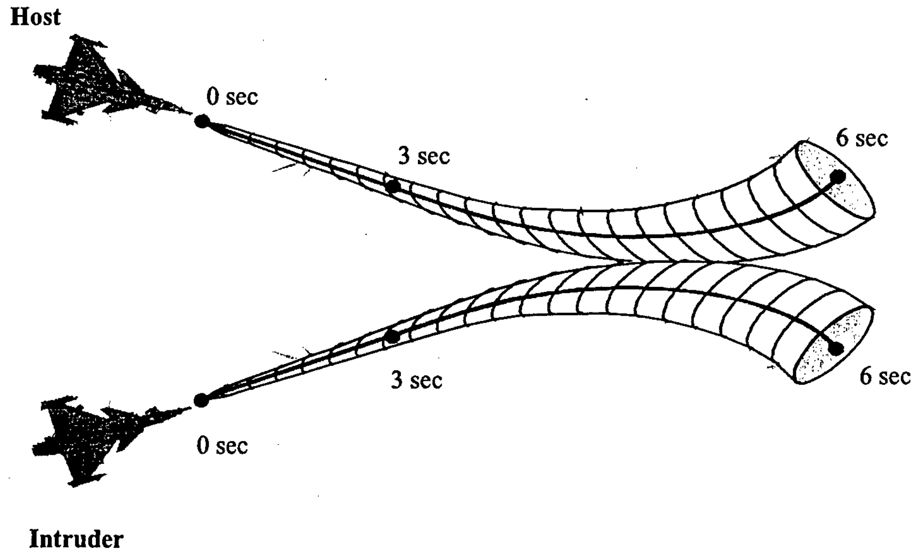


Figure 2. 6 seconds long flight envelope confining flight paths associated with the 3 possible maneuvers

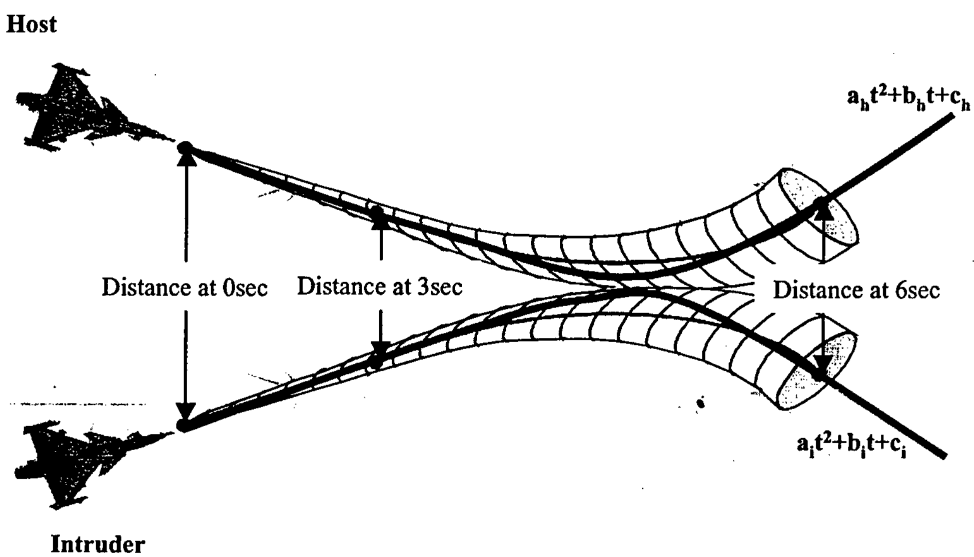


Figure 3. Quadratic Curve Fit using 0, 3, 6 seconds position along a flight path.

Since each approximated flight path is represented by a second order polynomial function in time of the form

$$a.t^2 + b.t + c \qquad (1)$$

the necessary condition for optimality applied to a norm of relative position

$$d/dt \, \|(a_i-a_h)t^2+(b_i-b_h)t+c_i-c_h\| = 0 \qquad (2)$$

yields time instance Tmin at which the minimum separation occurs. The advantage of using a quadratic curve fit is that Tmin is obtained by solving a cubic polynomial equation whose analytic solution is readily available. With this Tmin so determined, it is an easy exercise to find the minimum separation distance.

To find the best combination of escape maneuvers between the host and intruders, the minimum separation distance for each possible combination of escape maneuvers is first calculated. Here, each aircraft has three possible choices of escape maneuver in the optimization process. The first one is roll with a bank angle selected in the previous iteration together with simultaneous pull with the maximum allowable normal acceleration (Nz) command. The second and the third ones are rolls with plus and minus delta bank angle around the first one, respectively, together with the simultaneous pull with the maximum allowable Nz command. Thus, there are nine possible combinations of escape maneuvers between a host and an intruder. In addition, this process is repeated for each intruder. Therefore, three (the maximum number of intruders) times nine (number of possible combination of escape maneuver between a host and an intruder) minimum separation distances are calculated. Among all the possible maneuver combinations, the one which gives rise to the minimum reciprocal sum of minimum separation distances is selected as the optimal combination of the escape maneuvers. The reason for minimizing the reciprocal sum of minimum separation distances as opposed to maximizing the sum of minimum separation distances is to penalize the combinations of the escape maneuvers that provide the worst separation distances.

2.2 Escape Maneuver Activation and Termination

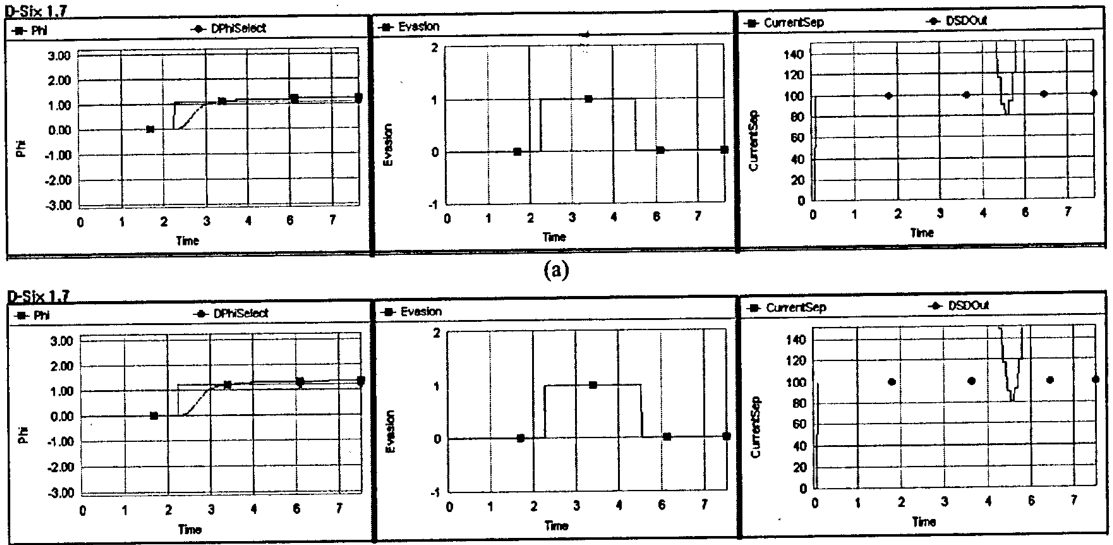
The escape maneuver determined via the optimization process is activated when the predicted minimum separation distance becomes smaller than the prescribed minimum safety distance. To increase the accuracy of this prediction, the distance between the host and the intruder is recalculated based on the flight path which is curve fitted by cubic spline using the position and velocity information at 0, 3, and 6 seconds. The escape maneuver is terminated when the separation distance starts increasing, i.e., when the minimum separation has been reached. This satisfies system requirement No. 1 discussed earlier.

3. Simulation Results

To evaluate the logic in the algorithm and make assessment of the performance, the results from non-linear simulation in different collision scenarios are discussed. Basic collision scenarios such as head-on, trail, and beam (90 degree aspect angle) are used to test the performance of the algorithm. A PC-based desktop flight simulator called D-Six (a product of Bihrle Applied Research, Inc) is used to perform simulation. D-Six executes the Auto ACAS algorithm using non-linear 6 DOF equations of motion.

Head-on Collision Scenario: To evaluate a case of high closure rate, a head-on collision scenario was simulated. Host and an intruder both fly at Mach 0.65, 7 km altitude in a head-on collision course, resulting in 430 m/sec closure rate. Figure 4 shows the resulting optimal combination of escape maneuvers (far left), escape maneuver activation status (middle), and the separation distance between the host and intruder (far right). In the far left plots, bank angle and ACAS roll command are shown with a blue curve and a red curve, respectively. It can be seen that both aircraft turned 1 radian or about 60 degree right to avoid collision. In the middle plots, the status of escape maneuver activation is shown where 1 means active and 0 means non-active. The plots show that it took a little over 2 seconds to complete the escape maneuver. In the far right plots, separation distance (blue) is shown against the prescribed minimum safety distance (red). The plots for both the host and intruder show that the minimum separation achieved is 80m against the minimum safety separation of 100m, resulted in 20 % penetration.

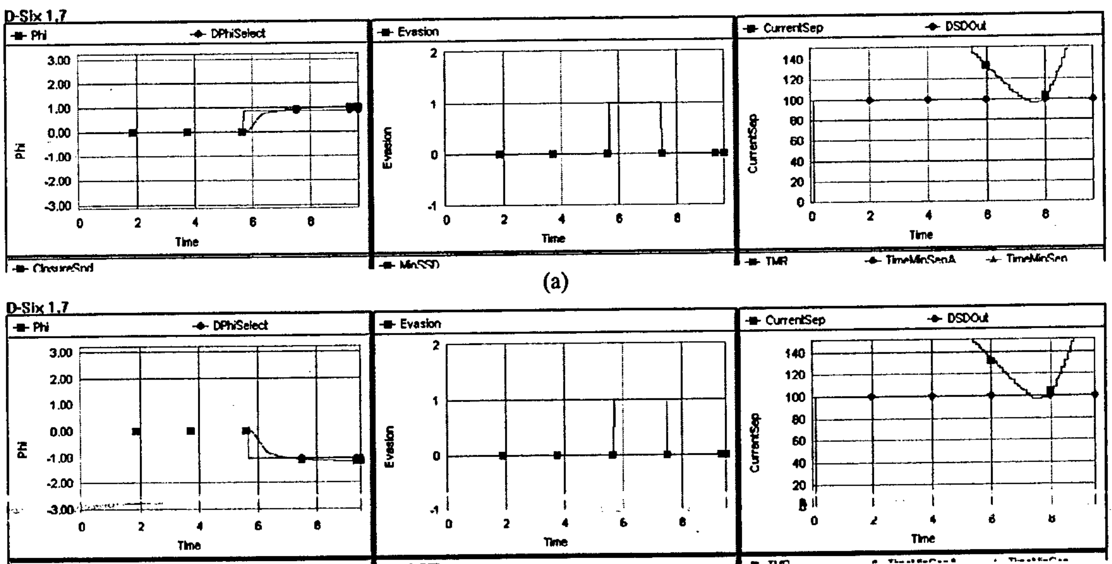
Trail Collision Scenario: To evaluate a case of low closure rate, a trail collision scenario was simulated. The host flies at Mach 0.7, 7 km altitude, while the intruder flies at Mach 0.65, 7 km altitude, resulted in 30m/sec closure rate. The far left plots in Figure 5 shows that the host and intruder chose opposite direction for roll of about 60 degree. The middle plots show that time to complete the escape maneuver is less than a second, much less than that for the high closure rate case. The far right plots show that the minimum separation achieved is about 100m, almost no penetration into the safety bubble.



(a)

(b)

Figure 4. Head-on Collision Scenario – (a) Intruder, (b) Host



(a)

(b)

Figure 5. Trail Collision Scenario – (a) Intruder, (b) Host

4. Conclusions

Simulation results to date indicate that the Automatic Air Collision Avoidance System presented in this paper meets the basic requirements. In particular, it seems promising that the system can provide mid-air collision protection for fighter aircraft during combat training and formation flight without interfering with the pilot's mission. There is more logic developed and implemented in the system than is presented in this paper such as logic to accommodate time delay, data dropout, failure mode, close formation flight and so on. Discussion on these issues is deferred to a future paper due to limited space. The system will be flight tested in July, 2003.

Reference

[1] Ba Nguyen, Arthur Barfield, Yutaka Ikeda, Carl-Olof Carlsson, "Preliminary Simulation Predictions of Nuisance Criteria for an Automatic Air Collision Avoidance System", The 9th St. Petersburg International Conference on Integrated Navigation Systems, May 2001.