Proceedings of the
44th IEEE Conference on Decision and Control, and
the European Control Conference 2005
Seville, Spain, December 12-15, 2005

Auto-ACAS - Robust Nuisance-Free Collision Avoidance

Bengt-Göran Sundqvist, Saab AB

***Abstract*—During 2000 - 2004, a concept for an Automatic Air Collision Avoidance System (Auto-ACAS) has been developed and demonstrated in simulations and flight test with F16 aircraft. The system performs coordinated automatic evasive maneuvers when collisions are imminent, still allowing the pilots to fly the aircraft according to regulations without creating nuisance activations. The performed simulations and flight tests have shown successful results and the concept is proven to be suitable for use in modern fighters as well in UAV's and other platforms. The ability of the system to handle complex situations with multiple involved aircraft performing highly provocative maneuvers has been above all expectations.**

We here briefly present the system design, testing and conclude the work done in the joint Swedish and USA program.

I. SYSTEM REQUIREMENTS

In the beginning of the program three major requirements on the system were decided:

1. It shall perform an automatic escape maneuver.
2. It shall have fail-safe operation.
3. It shall be nuisance free.

The first requirement indicates use of the flight control system (FCS). The second requirement indicates thorough monitoring of flight critical parameters used and inhibition of the system if safe operation can not be ensured. The third requirement rules out systems similar to TCAS which presents an advisory function, alerting well in advance in case of a potential collision.

Furthermore a number of design requirements were identified e.g.:

1. It shall handle asynchronic operation between algorithms in different aircraft.
2. It shall handles large (~0.3 sec) varying delays between algorithms in different aircraft.
3. It shall have low computational load, enable execution in the avionics system.
4. It shall have predictable "pilot-like" response.

II. CONCEPT

The system was to use the available hardware in a modern fighter, such as the flight control system, a blended inertial and GPS navigation solution and a data link for communication (still enabling use of other sensors for Out-of-Network capability).

A. *The Claim Space method*

The developed 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 in a predetermined way by the Auto-ACAS algorithm using the FCS, whereas the probable trajectory is affected by the change in pilot commands. The size of the claimed space is determined from knowledge of the wingspan, navigation uncertainty and accuracy of the predicted escape trajectory compared to the one the FCS 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. 1. 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 FCS to make the aircraft follow the stored trajectory.

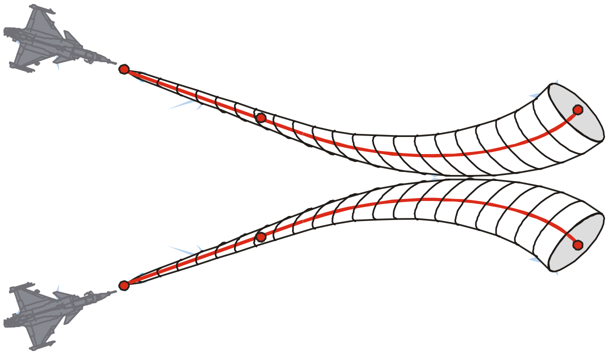

Fig. 1. Collision detection using predicted escape maneuvers

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.

B. *Handling of time delays*

Due to the time delays (varies between 0.1 and 0.5 seconds) between the algorithms computed in the different aircraft the transmitted escape trajectory initially contains a

0.3 seconds predicted flight path after which the escape trajectory is added. As this prediction is done in the own aircraft, current accelerations and angular velocities as well as velocities can be used in the prediction.

To be able to compensate for the rest of the asynchronous delay, the data contains the time when it was produced. The received data from the other aircraft is dead reckoned to current time using transmitted velocity vector only. This means that no dead reckoning is needed if the actual time delay is 0.3 seconds between two Auto-ACAS algorithms. The data used for the own aircraft (own claimed space) in each iteration is chosen as the one having the closest timestamp to the other aircraft data used in that specific iteration. Thus time corresponding data is used in all aircraft which forces all algorithms to use the same data and thus executing the escape maneuvers at the same time.

C. Failures affecting the algorithm

Data dropouts, due to errors identified through parity check of the link data, "shadowing" or misalignment of the antennas etc., causes the established communication between two algorithms to disappear. To allow dropouts, even close to activation, and still supply protection against collision, the change of escape direction is limited as a function of actual distance and estimated time to activation. This limitation of change is balanced by the requirement that the escape maneuver shall be optimal and thus having the ability to change fast. At data dropouts the claimed space for the aircraft which the communication is lost for is also expanded in the own aircraft to handle unknown maneuvering and change of escape direction of the other aircraft.

Navigation degradation, due to loss/degradation of GPS, air data sensors, inertial navigation system or terrain navigation etc. is inherently handled by the algorithm. As the size of the claimed space is computed using the current navigation uncertainty a degradation of navigation performance only expands the claimed space according to the new uncertainty.

Failures in sensor data, used in the FCS to fly the escape trajectory, force the algorithm to transmit the predicted trajectory (not the escape trajectory) and set failed state over the link. This will cause other aircraft to avoid the aircraft with FCS failure.

Failures in other sensor data, used in the computation of the predicted escape trajectory, is handled dependent of how eminent the activation is. The predicted trajectory is always transmitted but close to an activation (collision) the FCS of the failing algorithm directly activates the escape maneuver.

D. Formation flying logic

To enable aircraft, equipped with Auto-ACAS, to rejoin and fly in formation the algorithm contains logic, which inhibits the activation of Auto-ACAS against aircraft who fulfill the inhibit condition in Fig. 2. (The condition also contains a hysteresis to be less sensitive to noise in the transition phase). This condition was set using data from a test pilot project performed at Edwards AFB, Ca. in which the students performed rejoin maneuvers of different aggressiveness.

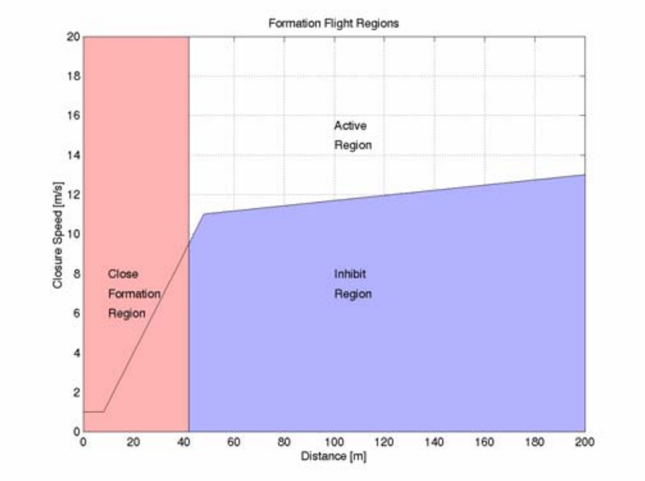

Fig. 2. Inhibit condition in Formation Flying Logic

If the distance between the aircraft becomes less than the claimed spaces at the first point along the escape trajectory, Auto-ACAS is inhibited for all aircraft. This is done to ensure that Auto-ACAS does not activate a maneuver, which could cause a collision. An activation of a maneuver when the algorithm is not sure of the relative position of the aircraft (i.e. they are inside each others position uncertainties) might turn the aircraft into each other.

When Auto-ACAS is totally inhibited in the aircraft fulfilling this last condition, the algorithm in all other aircraft are set to yield to this formation. This includes boosting their claimed space and re-computing/predicting the trajectory of the formation to be along the velocity vector of the formation. This makes aircraft not flying in formation do all of the maneuvering in case of an activation.

E. Out-of-Network adoption

Information, received by other means than the dedicated Auto-ACAS link service, regarding other aircraft is handled similar to In-network data. A predicted trajectory is predicted from the different sensor data and a claimed space is constructed from the measurement uncertainties of the different sensors. Nuisance free operation can of course not be guaranteed against these Out-of-Network aircraft as their claimed space of tends to be large.

F. UAV adaption

To ensure that manned aircraft have right of way when they are in a collision potential with unmanned vehicles the algorithm transmits the type of aircraft it is hosted on. There are currently four classes defined: {UAV, fighter, heavy, non-maneuvering}. The algorithm in an aircraft with lower class avoids the predicted probable track of a higher, whilst the algorithm in a higher aircraft avoids the transmitted escape maneuver of the lower class. This way the lower class vehicle activates earlier, while the higher class still activates if the basic Auto-ACAS concept requires it.

G. Potential fields of improvements

A number of fields have been identified to improve the Auto-ACAS concept, e.g.:

1. Engaging a capture mode after the completion of an Auto-ACAS activation. To save the vehicle from a potential mid-air collision is not enough if the systems e.g. leaves the aircraft nose low in bad weather conditions
2. The Integration of Ground Collision Avoidance System (GCAS) to ensure that the selected escape maneuver does not cause ground collision potentials.
3. Expanding the escape maneuvers to incorporate bunting maneuvers (negative load factors) will improve nuisance potential and enable safe operation closer to the ground

H. Algorithm testing

During the development phase the changes to the algorithm were tested and verified in both pilot model controlled and manually stick controlled simulations. Desktop simulators with flexible pilot models were used to check changes between algorithm versions and to study parameter variations both inside the algorithm and in other models affecting the algorithm. At these simulations thousands of equivalent test cases were run each time in batch mode. Stick controlled simulations were run both in PC based desktop simulators (D-SIX) and software dome simulators.

A couple of larger simulation sessions were held when all the development parties gathered and pilots from the two countries put the algorithm to the test. Between these sim-sessions the developers had time to evaluate the captured data, make modifications to correct undesired features and implement new functionality to further meet the requirements of the program. The new functionality included logic for formation flying, system wide integrity management, Integrity management on link data, usage of global coordinate system and redefinition of escape direction from absolute to relative to enable safe activations at nadir and zenith.

III. FLIGHT TEST

The flight test planning and preparation was done in parallel to the algorithm development and testing. The people responsible for the flight tests participated during the sim-sessions and the results and knowledge were passed between all involved personal.

In preparation to flight test a build up in testing was performed, where the test objects became closer to the real ones the number of test cases were gradually reduced. As the costs for the tests rise, the efficiency decreases and between all steps of increased test fidelity the performance of the algorithm was verified against the previous. If the performance of the algorithm could not be recreated in the next step this test case was removed for the test matrix for the next level. This resulted in a startup containing ~10000 simulations in stick controlled desktop simulations, ~4000 simulations in Hardware in the loop rigs (HILS), ~600 flight tests runs where the real aircraft was flown against a simulator on the ground and ~100 real runs involving two aircraft.

At the demonstration of a system which goal is to increase safety and reduce the number of mid-air collision the evaluated system itself can not be used to ensure flight safety. In the Auto-ACAS project the pilots of the aircraft were responsible for safety during the tests. To ease this task a number of preparations, methodology and tools were developed. All personnel scheduled to be involved in the testing underwent control room training integrated with the testing in the HILS. Tools for supervising the algorithm performance were integrated on the computers in the control room and during the tests these were feed with telemetry data from the test aircraft. The aircraft were modified with test specific HUD symbology, redundant high access means to disable the algorithm, modifiable exclusion zones - directions in which the activation would not be executed even if the algorithm desired it. The tests themselves were also performed in a buildup manner regarding the closure speed, relative heading, size and orientation of the offsets of the aircraft in the nominal point of minimum distance and safety buffer between the claimed spaces.

IV. CONCLUSIONS

The approach to detect collisions by comparing predicted escape trajectories, previously applied in the implemented and tested Automatic Ground Collision Avoidance System (Auto-GCAS), works well in avoiding other maneuvering aircraft. The optimization in the Claim Space method gives coordinated escape maneuvers at coordinated times.

The current implementation of the algorithm gives reliable, predictable results both in low and high dynamic scenarios. No nuisance is observed in simulations when aircraft are maneuvering outside the safety zones currently used in the Swedish Airforce and activations are performed in cases where collisions would be unavoidable.

The Auto-ACAS algorithm is generic in the sense that it can accommodate different aerial vehicles such as fighters, transports, tankers, UAVs etc. with a minimum of aircraft specific adaptation. Any aircraft that can predict its avoidance trajectory 5-10 seconds ahead and communicate that information via a data link can be protected with Auto-ACAS.