DEVELOPMENT AND INTEGRATION OF HUMAN-CENTERED CONFLICT DETECTION AND RESOLUTION TOOLS FOR AIRBORNE AUTONOMOUS OPERATIONS

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Today's crowded airspace burdens both the pilot and controller with a heavy workload pertaining to the maintenance of conflict-free flight. Conflict detection and resolution (CD&R) tools have become a key element in modern flight systems and future airspace concept simulations. In this paper we describe an automated resolution tool that was developed at NASA Ames Research Center as part of an experimental evaluation of the Distributed Air-Ground concept. The tool is based on an analysis of conflict geometry and was developed as an intent (i.e. flight plan) resolution system. A key simplifying concept used in the development of airborne automated resolutions is the notion of "Rules of the Road" - a set of rules that uniquely assigns responsibility for the mitigation of a conflict. This paper outlines the challenges in developing such an automated resolution tool, as well as the lessons learned and the limitations observed.

Introduction

Free flight allows aircraft greater flexibility in en route maneuvers but shifts the responsibility for maintaining safe separation with other aircraft onto the pilot. With the shift in responsibilities, a flight deck tool is required in order to aid the flight crew with the tasks of maintaining separation. This tool should detect conflicts far in advance so that pilots can respond to conflict alerts in a strategic manner. This approach is in contrast with the reactive, tactical response elicited by the current Traffic Collision Avoidance System (TCAS), whose alerts are short range and immediate. To study this concept, the Flight Deck Display Research Laboratory at the NASA Ames Research Center has developed a Cockpit Display of Traffic Information (CDTI) system that is integrated with a Conflict Detection and Resolution (CD&R) tool. Based on flight path "Intent", the CD&R tool detects conflicts up to 12 minutes in advance and automates conflict resolutions by presenting to the pilot a list of pre-computed maneuvers that will result in a "de-conflict" prior to the time of loss of separation (LOS). In June of 2004, as part of the Distributed Air-Ground Traffic Management (DAG-TM) research program, research teams at the NASA Ames Research Center and Langley Research Center conducted a joint experiment to investigate the operational feasibility of the En Route Free Maneuvering concept, also known as Concept Element 5 (CE 5). Central to the CE 5 study was the idea of increasing airspace throughput by shifting more responsibilities to the airborne systems for maintaining separation. In particular, aircraft equipped with CD&R tools and flying autonomously are responsible for maintaining separation from other autonomous aircraft and from aircraft that are under Air Traffic Control (ATC) management ("managed" aircraft). The sections below discuss the implementation of the CD&R tool, experimental trials, evaluation, and future research and development in this area.

Implementation

Design Goals

The overall objective is to cultivate a flight deck system that will promote the efficacy of free flight. The effectiveness of CD&R tool from a human-factor perspective can be studied using a laboratory prototype of the system. Long term issues involving CD&R tool-design for the next generation flight decks can also be addressed. The primary design goal is that it must be human-centered, and an extension of a pilot's decision faculty. It should require no attention from the pilot in the absence of a conflict alert and it should not inundate the pilot with complex resolution activities when conflicts are detected. This system will serve as a strategic planner that provides the pilot with greater degree of freedom in terms of time and maneuver-options when confronted with conflicts. A near instantaneous response to a user action is crucial to the effectiveness of a CD&R tool. Therefore, system performance is a major consideration.

Conflict Detection Algorithm

The conflict detection algorithm in the CD&R tool is an adaptation of the methods described by Yang and Kuchar (1997, 1998). The algorithm uses aircraft intent information to propagate current states forward in time. These projected flight trajectories are then used to search for conflicts with the ownship (the observer's aircraft hosting a CD&R tool). A conflict is defined as an incident in which the ownship's protected zone is penetrated by another aircraft (intruder). The protected zone is a cylindrical volume of space 5 nm in radius and 2000 feet in height. With the ownship at the center, the protected zone is projected out along its trajectory while searching for conflicts with other aircraft.

The core of the algorithm is built based on a probabilistic model, but it can be configured to become a deterministic model at run-time by reducing the sampling rate to N=1.

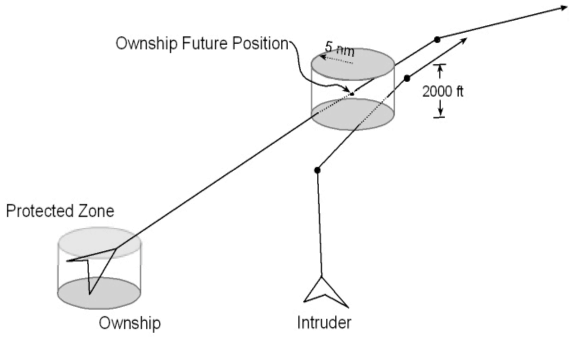


Figure 1. A conflict occurs when intruder aircraft penetrates the ownship's protected zone.

In the probabilistic approach, Gaussian and non-Gaussian distribution errors are introduced into the position, speed, and heading components of the aircraft states to model trajectory uncertainties. A Monte Carlo method is used to simulate the perturbed trajectories over N iterations. The probability of a conflict is the number of detected intrusions (or "hits") divided by N.

With upwards of 300 aircraft to process in the simulated airspace, performance is a primary consideration. Performance issues are mitigated in various ways. A number of filters are applied in order to screen out unlikely conflict candidates early in the process. Load management is accomplished through configurable sampling rate. A sampling rate of one second with 500 Monte Carlo iterations has been found to provide satisfactory results when combined with sample filtering. Using a 3.2 GHz dual processor and high speed graphic card at each simulation station, the system CPU budget is 25% for CD&R while graphical computation and other processes take up another 40%. Finally, the CD&R system is a standalone multi-threaded component; it can be deployed independently on a separate computer system to increase processing speed.

It should be noted that the solutions (computed conflicts) must be invariant. Specifically, a conflicting aircraft pair should see the same alert attributes (situational Awareness (SA) level, time to loss of separation (LOS), etc) from both sides.

Alert System and Symbology

Alerts are presented to the pilot through an escalating progression of alert conditions instead of an all-or-nothing approach, as would be the case for a TCAS resolution advisory. Alerts are categorized into three SA levels, with SA3 being the highest urgency and loss of separation imminence, and SA1 the lowest. In the probabilistic approach, an SA level is assigned by weighting the probability of a conflict with the corresponding Time Remained Prior to Loss of Separation (TLOS). The result is a mapping table shown in Figure 2.

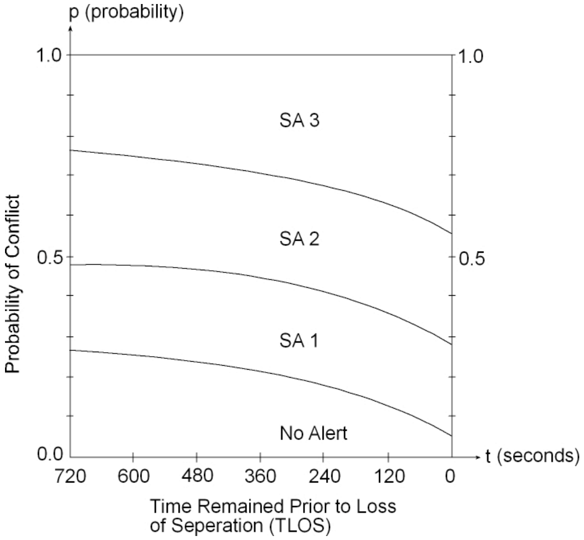


Figure 2. Assigning SA levels in a probabilistic model - Mapping of probability against TLOS.

Since uncertainty increases with time and distance in a predictor system, the probability of a conflict is therefore inversely related to the distance and time to the point of LOS. It is precisely this characteristic that facilitates a multi-leveled alert system. The probability of conflict becomes higher as aircraft approach LOS. Inspection of Figure 2 shows that an SA1 alert indicates medium probability with long TLOS to low probability with short TLOS; an SA2 alert indicates moderately high probability with long TLOS to medium probability with short TLOS; SA3 alert indicates high probability in general.

In the deterministic approach (N=1), no uncertainties are introduced. The multi-leveled transition depends on TLOS alone; staged at twelve minutes, eight minutes, and four minutes for levels SA1, SA2, and SA3 respectively.

Alert presentation to the crew employs various visual and auditory cues. At SA1, the ownship's symbol (default color is magenta) and the intruder's symbol (default color can be blue, green, or white) both turn to amber on the CDTI. If the intruder aircraft is out of display range, the "Alert" button "lights up" in yellow to alert the pilot that the intruder aircraft is not in view. By clicking on the "Alert" button, CDTI automatically zooms out to a larger range that brings the intruder aircraft into view. When the alert level escalates to SA2, an amber halo is superimposed on the conflicting-aircraft symbols. At SA3, an amber predictor pulse is projected along the flight paths, and an amber protected-zone-ring is projected out to the LOS position. Also at SA3, an audible chime is sounded. This transition from a subtle visual stimulus to a more salient one coupled with an audible sound is designed to cue the pilot as to the degree of urgency, thereby prompting the pilot to prioritize tasks.

Figure 3. CDTI showing an SA3 alert level. Alert button lights up in yellow (bottom, second from left).

When SA1 first appears at roughly twelve minutes prior to LOS, alert presentation cues the pilot that there is ample time to act and more options are available if action is taken immediately. When the alert level escalates to SA2 at roughly eight minutes to LOS, the pilot is reminded that there is a moderately high probability that a loss of separation is going to occur, and that the situation should be resolved within four minutes. When the alert level escalates to SA3 at roughly four minutes to LOS, a loss of separation is imminent - something has to be done immediately. Figure 3 depicts an SA3 alert level in the CDTI.

Concept of Conflict Probes

A probe is defined as a deliberate search for conflicts along an "Intent" trajectory. The primary "Current Probe" probes the current intended route and is active at all times. However, the CD&R tool has two additional probes: the "RAT (Route Analysis Tool) Probe" and the "Vector Probe". A dedicated Monte Carlo simulation powers each probe. The RAT is an independent component of the CDTI that provides a graphical user interface for modifying a flight path by inserting, deleting, and moving waypoints and leg segments of the existing flight plan. A detailed presentation of the RAT is beyond the scope of this paper. It will suffice here to characterize the RAT as a strategic planner for route modifications. When a modified route is proposed using the RAT (RAT route), a new probe is set off to search for conflicts along the proposed flight plan, thereby providing a level of confidence that the route is conflict free before committing to it.

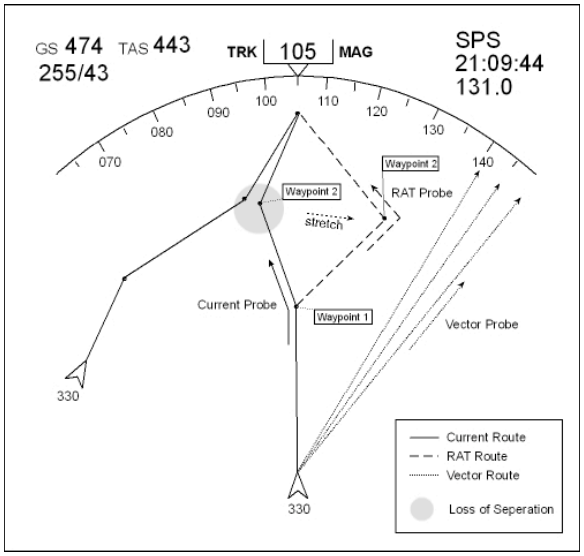


Figure 4. Current, RAT, and Vector Probes along their respective routes on the CDTI display.

The Vector Probe allows a pilot to probe for conflicts along an arbitrary heading. Dialing the heading on the Mode Control Panel activates the Vector Probe. A probe is set off to search for conflicts along the heading line as the pilot sweeps it across the display. This probe boosts the effectiveness of the CD&R tool, allowing it to support a free-flight environment in the truest sense. Figure 4 depicts the three conflict probes on the display.

Resolution Algorithm and Automation Display

The conflict resolution algorithm is an adaptation of the geometric optimization method presented by Bilimoria (2000). Efficient conflict resolution commands are computed for four different types of maneuvers: altitude change, speed change, heading change, and a combination of heading and speed change; these resolutions are presented to the pilot as proposed flight plans. For each maneuver type, two solutions with the least deviations from the nominal trajectory are selected. A maximum of eight solutions are provided when available. The computed resolutions are prioritized by their efficiency. As shown in Figure 5, a list of computed resolutions pops up when the "Res" button is clicked. The most efficient maneuver (least perturbation to the current trajectory) appears at the top of the list. The appropriate proposed flight plan is loaded into the RAT when the pilot clicks on one of the resolution options; this affords the pilot the opportunity to inspect and revise the selected resolution at will.

Figure 5. Display of automated conflict resolutions (enlargement shows 3 maneuver options).

In some cases, not all eight resolutions are available due to constraints such as TLOS, altitude restrictions, proximity of other aircraft, and FMS equipage (an FMS may not be able to implement a combined speed-heading maneuver, for example). The list of automated resolutions is dynamic. If no action is taken while the LOS point is approaching, these resolution options will expire one by one as they become invalid. The pilots can choose to ignore the automated resolutions and manually devise their own avoidance maneuvers.

The Rules-Of-The-Road Component (ROR)

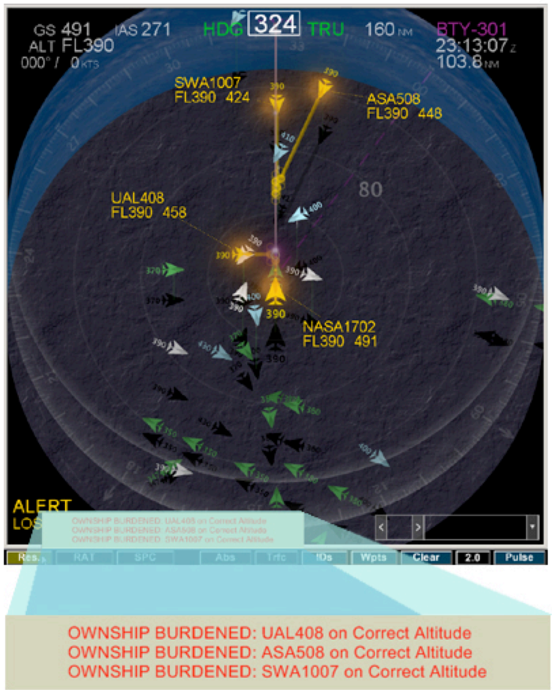
The outcome of conflict detection is expected to be invariant and symmetrical between aircraft. Specifically, conflicting aircraft pairs should receive identical alerts if they have deployed the same CD&R tool. This can potentially lead to a race condition when both aircraft execute avoidance maneuvers concurrently, which if uncoordinated, may result in further conflicts that could become un-resolvable. To mitigate such situation, the CD&R tool incorporated "rules of the road" - a set of rules designed for coordinating collision avoidance in VFR flight.

ROR is a component of the CD&R system that automates the application of rules to a conflict situation. ROR relieves the flight crew from the distraction of having to mentally analyze the situation and apply the proper rule to arrive at a right-of-way conclusion. The right-of-way issue is settled by means of *burdening settlement*. In other words, ROR analysis identifies which aircraft has the burden of resolving a particular conflict.

When a conflict is detected, ROR analyzes the flight plans and the flight states of the conflicting aircraft at the point of LOS. A set of hierarchically ordered rules is then applied sequentially. A rule is found applicable only if the following complemental condition is satisfied: one aircraft must be non-compliant while the other is compliant with respect to that rule. If a rule is found to be inapplicable, then the next rule is applied and so on until the complemental condition is satisfied. The non-compliant aircraft is said to be the burdened aircraft and will be responsible for making trajectory modifications in order to resolve the conflict. The outcome of ROR analysis is a *burdening settlement* advisory that is issued to the two aircraft. Each settlement is accompanied by a short phrase (reason) that cites the particular rule leading to the settlement. By this automation process, only one aircraft is required to take action to resolve a conflict, thereby mitigating the potential danger of a race condition early on. Figure 6 shows multiple *burdening settlements* issued by ROR during multiple conflicts.

To avoid ambiguities induced by highly articulated flight paths, the ROR rules are applied at the point of LOS. The following is the list of hierarchical rules implemented in the ROR (definitions of these rules as well as an in-depth treatment on ROR are presented by Johnson, Canton, Battiste, and Johnson. 2005):
- IFR/AFR rule
- Altitude Rule

- Vectored Rule
- Left/Right Rule
- Level Flight Rule
- Descend/Climb Rule
- Overtake Rule



OWNSHIP BURDENED: UAL408 on Correct Altitude
OWNSHIP BURDENED: ASA508 on Correct Altitude
OWNSHIP BURDENED: SWA1007 on Correct Altitude

Figure 6. Display of burdening settlements during multiple conflicts (enlargement shows reasons).

Flight Deck Integration

To emulate full flight deck functionality on different platforms for the CE5 study, the conflict detection-capable CDTI was integrated into the Advanced Concepts Flight Simulator (ACFS) as well as the Multi-Aircraft Control System (MACS). The ACFS is a 6-degree-of-freedom full mission B737 flight simulator in the Crew Vehicle Systems Research Facility (CVSRF) at the NASA Ames Research Center. The MACS is a desktop computer flight simulation program that emulates the B777 flight deck controls. It was developed by the Airspace Operation Laboratory (AOL) at Ames (Prevot, 2002).

Experimental Trials and Evaluation

Conflict Detection and Alerting

The probabilistic conflict detection algorithm was evaluated during a pre-CE5 "shakedown" period. Conflicts were detected and pilots alerted through the aforementioned multi-leveled system. The escalation of alert levels from SA1 to SA3 followed a main evolutionary trend in the Probability-TLOS domain. This evolutionary trend is labeled as the "Main Sequence" in Figure 7. A very small number of alerts entered the main sequence midway from outside the shaded region. Those alerts manifested themselves as "pop-ups". Pop-ups were problematic in that they were likely already in alert level SA3 when they first appeared. This left the flight crew very little time to respond strategically.

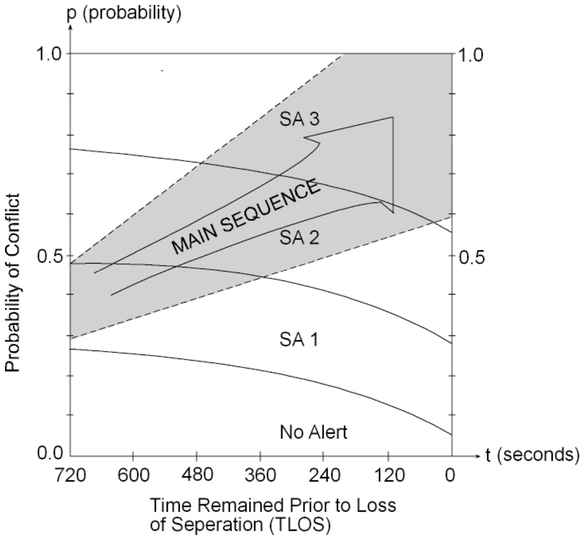


Figure 7. Evolution of alert levels along the Main Sequence.

Another artifact observed was alert dithering (i.e. a fluctuating alert level). This proved distracting to the pilots. Both pop-ups and dithering artifacts can be attributed to incompatible simulator behavior from different simulation platforms, the absence of a network wide time-synchronization system in the distributed simulation, and to a lesser extent the low density sampling of Monte Carlo space (500 iterations per cycle). Further study is needed in these areas.

A third artifact of the probabilistic algorithm was the violation of the aforementioned invariance. There were a very small number of cases in which the conflicting aircraft pair did not receive the same alert at precisely the same moment. This inconsistency was due to two probabilistic systems taking random samples independently (therefore, non-identical variance), as well as system messaging delays and the absence of a time-synchronization system. Further study is warranted in this area.

As an immediate remedy to these artifacts (and to further improve system performance), the conflict detection algorithm was re-configured to probe deterministically (by sampling the Monte Carlo space once per cycle). This was the version of the CD&R that went into the actual CE5 experiment.

Automated Conflict Resolution

The automated conflict resolution was implemented incrementally leading up to the pre-CE5 shakedown. While it worked well in simpler forms, its performance was less than ideal when more complex maneuver types were added to the solutions. The increase in complexity was compounded by the generation of new flight plans that were incompatible with other CDTI components. The result was less than ideal solutions and poor system performance. A decision was made to disable the automated conflict resolution feature for the actual CE5 experiment, and continue to resolve conflicts manually.

Rules of the Road Automation

ROR performed flawlessly during the shakedown and the actual CE5 experiment. It accurately applied rules and issued burdening settlements that could be consistently verified by the conflict aircraft pair. As a result, resolution maneuvers were made only by the burdened aircraft during autonomous-autonomous encounters, eliminating right-of-way ambiguities. Together with the deterministic conflict detection and alert, ROR fulfilled the role of the airborne self-separation tool for the autonomous flights during the CE5 experiment.

Conclusion and Future Work

Although the automated conflict resolution tool was not yet matured at the time of the CE5 experiment and had to be disabled, the overall CD&R-capable CDTI proved very successful. The Current Probe, the RAT Probe, the Vector Probe, and the ROR all contributed to enhancing the pilot's ability to resolve conflicts manually, a result consistent with previous work. It has been shown that pilot-generated resolutions are more effective when aided by decision support tools (Johnson, Bilimoria, Thomas, Lee, and Battiste, 2003).

While the concept and the design of the automated conflict resolution is sound, more work will be done to handle the complexity of multiple maneuver types and seamless interface with other CDTI components.

The dithering and the pop-up alert artifacts of the probabilistic conflict detection algorithm could be addressed with enhancements to the algorithm, the overall messaging system, and possibly with a denser Monte Carlo sampling. A new alert level mapping scheme should also be explored.

Finally, although the ROR performed flawlessly during the CE5 and handled all right-of-way issues, there was no provision in place to handle the case in which no rule applied. This case currently always defaults to burdening the ownship. So far, it has not occurred in experiments, but if it does, it will lead to the race condition because both aircraft will be burdened. A new ruling scheme is being developed for this special case.

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