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DISTRIBUTED AIR / GROUND TRAFFIC MANAGEMENT EN ROUTE FREE MANEUVERING RULES OF THE ROAD: REQUIREMENTS AND IMPLEMENTATION FOR A SIMULATION OF EN-ROUTE SELF-SEPARATION

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National Aeronautics and Space Administration's (NASA) Distributed Air Ground Traffic Management (DAG-TM) program has recently investigated a concept called "En-route Free Maneuvering" as a proposed solution for expanding airspace capacity limits. A critical element for this concept is conflict detection and resolution (CD&R) using the 3D cockpit situation display (CSD). The only fielded system performing some of this function is the Traffic Alert & Collision Avoidance System (TCAS), a radar-based alerting system used by most commercial aircraft for collision detection and avoidance. TCAS is inappropriate for an en-route self-separation application due to its reactive nature, and inherent lack of flexibility. Therefore, a new system was designed with improved intent information in the form of 4D flight plans, broadcast and shared amongst en-route aircraft, which in turn allowed these aircraft to detect and resolve conflicts well in advance of a projected conflict. A key element in this approach is ensuring that *burdening*, the assignment of final responsibility for conflict resolution is clearly assigned to the aircraft not in right-of-way. The basis for this burdening is called the *rules-of-the-road* (ROR), a term taken from the rules designed for guiding collision avoidance in VFR (visual flight rules). Given the potential complexity of determining burdening assignment, the automation described herein computes assignment using these rules, and then notifies the crew if it has the right-of-way or is burdened to resolve the conflict.

Introduction

DAG-TM is a proposed solution for expanding airspace capacity limits. It alters the roles and responsibilities of the stakeholders – airlines and air-traffic control - to permit more user-preferred routing, increased flexibility, increased system capacity, and improved operational efficiency. It is based on the fundamental premise that the National Airspace System (NAS) participants can be information suppliers and users, thereby enabling collaboration at all levels of traffic management decision-making. The success of this proposed, future environment may depend greatly on new human-centered operational paradigms enabled by technological and procedural innovations (Raytheon ATMSDI Team. 2004).

Air travel has advanced from an uncontrolled "see and avoid" environment, to vastly increased numbers of aircraft tightly controlled by ground facilities. As it moves on into the next generation, one that supports an increase in capacity and free flight, distributed control is suggested as a viable air traffic management (ATM) model. Distributed control refers to the delegation of responsibility between the air traffic service provider (ATSP) and the flight crew, defining whom maintains separation assurance. In this environment, the old rules-of-the-road that supported aircraft in a visual-only airspace will no longer work effectively to ensure safety of flight. A new set of rules for 'autonomous aircraft' that share separation responsibilities in a free flight environment are required.

Current Operations

In current operations, often-used flight rules are virtually second nature to the pilot who is being managed by air traffic control. Pilots flying commercial class aircraft are less likely to need to refer to the visual flight rules although there are rules that become ingrained much in the same manner as a driver interacts with traffic laws while driving a car. Specifically, visual flight rules are a set of regulations that a pilot may operate under when weather conditions meet certain minimum requirements. Under VFR, the pilot controls the attitude of the aircraft by relying on what can be seen out the window, although this may be supplemented by referring to the instrument panel. A pilot flying under VFR is usually required to stay a specified distance away from cloud formations and remain in areas where the visibility meets minimum requirements. In VFR, the pilot is responsible for seeing and avoiding other aircraft, terrain, and obstructions such as buildings and towers. Being in contact with air traffic control is optional in most airspace, and the pilot is usually allowed to select the course and altitude to be flown based on VFR direction of flight and altitude rules (http://www.fact-index.com). The pilot may also choose to navigate by reference to visual landmarks and/or utilize electronic navigation aids. In a distributed control environment, the pilot would also be responsible for maintaining separation from other aircraft.

Current commercial transport operations utilize a collision avoidance system called Traffic Alert & Collision Avoidance System (TCAS). TCAS scans radar information of proximal traffic to determine distance and closure rate. If TCAS detects that an aircraft's distance and closure rate are potentially threatening to Ownship, it will generate a traffic advisory (TA) or a resolution advisory (RA) to the crew. Both advisories are displayed on the TCAS display screen and are accompanied by an auditory alert. If necessary, TCAS will compute a pitch command to avoid collision. At this time, TCAS is limited to vertical guidance and cannot coordinate aircraft performance standards into the resolution advisories. With TCAS II, the pitch commands are coordinated with the other conflicting aircraft – up to three **-** to avoid escape maneuvers in the same direction.

An inherent problem with TCAS is that it is reactive and involves little planning on the part of the pilot. A resolution advisory provides the pilot with a 25-second response time before loss of separation (LOS). TCAS logic does not incorporate flight path intent and as a result, when crews respond to a TCAS RA, they are instructed to perform either a vertical maneuver or to remain at current altitude. A suggested vertical maneuver may send the conflicting aircraft off their intended flight path and unexpectedly into another ATC sector. And, because TCAS does not have flight path information, false alerts are frequent in busy, high workload terminal areas.

The TCAS system has been a tremendous asset, however, the free flight environment may be one in which the most effective and efficient resolutions are based on *planned* maneuvers, which require information about aircraft intent. Therefore, in the least, TCAS will require some form of supplement. This supplement should alleviate the problem of radical maneuvers by providing the crew with critical time-based information and the ability to resolve potential conflicts without drastic maneuvers off their published flight path. When a potential conflict is presented to the crew in a timely manner, they can resolve it by performing the necessary deviations to the flight path that do not compromise flight safety or integrity.

Simulation Environment

The goal of the NASA human-in-the-loop simulation was to investigate the feasibility and operational benefits of a concept element (CE) under consideration as part of the DAG-TM program: *CE 5 En Route Free Maneuvering*. The work was completed as part of the Advanced Air Transportation Technologies (AATT) project under NASA's Airspace Systems program. The main purpose of *En Route Free Maneuvering*, is to reduce excessive, en route trajectory deviations that result from separation assurance and traffic flow management (TFM) conformance by distributing the responsibility for separation assurance. An additional benefit of distributing responsibility is that increases in capacity can be realized without placing an added burdening on the ATSP (Raytheon ATMSDI Team. 2004).

The simulation environment was distributed between NASA Ames Research Center and NASA Langley Research Center using the Aeronautical Datalink and Radar Simulator (ADRS) processor to link the facilities. The ADRS functions as the communication management and data distribution hub (Prevot, Palmer, Smith, Callantine. 2002). The DAG-TM airspace was a modified portion of the airspace in and around Fort Worth Air Route Traffic Control Center (ARTCC) (ZFW) and Dallas/Fort Worth TRACON. Participants consisted of seven controllers and 20 licensed pilots. All pilots were air-transport rated and had glass cockpit experience. All of the controllers and 10 of the pilots were located at NASA Ames.

It was important to test this concept in a mixed-equipage environment where some of the participating traffic would be under ATC control (labeled IFR), and others as free flight (labeled AFR for autonomous flight rules). All the AFR pilot-stations in the simulation were equipped with a CSD with datalink capability. Based on the distributed control model, if an AFR aircraft was in conflict with an IFR aircraft, the IFR aircraft always maintained right-of-way, *except* when the ATSP assumed verbal responsibility for conflict resolution. Because of the strategic nature of most conflicts either one or both of the two aircraft may maneuver for resolution, although only one will be 'burdened". This procedure allows maximum flexibility but assures that only one aircraft has the *responsibility* for resolving the conflict.

It was expected that all aircraft would remain on their broadcast (assigned) flight path during the simulation, only deviating if commanded by an ATSP. In addition, all AFR aircraft were required to implement only those flight plan changes that would not conflict with the broadcast intent of any other aircraft, IFR or ARF, well beyond the prescribed four minute to LOS window. All burdened AFR aircraft were expected to resolve any predicted high level conflict – notification of a less than four minutes to LOS alert - at least two minutes prior to LOS.

To assist the pilots with making route changes to resolve conflicts, their flight path can be viewed and easily manipulated on the CSD display. Future position over time can be shown with pulse predictor's running along planned paths of travel. Pilots can also display traffic in a 3D perspective view (Johnson, Battiste, Granada, Johnson, Dao, Wong, Tang. 2005). The route analysis tool (RAT) allows the flight crew to develop, evaluate, and implement potential flight plan changes (Granada, Dao, Wong, Johnson, Battiste. 2005).

Conflict Resolution with CSD Tools

In the DAG-TM studies, an aircraft operating as AFR in the en-route airspace is allowed to free maneuver. This involves the pilot generating user-preferred trajectory changes and instructing the aircraft's Flight Management System (FMS) to initiate the trajectory. On-board automation broadcasts the modified trajectory using Automatic Dependence Surveillance-Broadcast (ADS-B) to the ATSP and other aircraft. The flight crew has the responsibility to ensure that trajectory changes do not generate near-term conflicts (less than four minutes to loss of separation) with other aircraft. The CD&R provides predicted conflict alerts that require the flight crew to respond accordingly, either taking evasive action or allowing the intruder aircraft to maneuver depending on which aircraft is burdened to resolve (Canton, Refai, Johnson, Battiste. 2005). In contrast to the centralized air traffic management rules that govern IFR operations, in a free flight environment the rules are based on a distributed-control model that references and resolves all potential aircraft conflicts by determining right-of-way, ensuring the pilots participation in the decision-loop in a timely manner.

Normally an aircraft operating in IFR conditions is under the control of an ATSP at all times, with the ATSP retaining separation responsibility. In this study, IFR flights were managed through voice and datalink clearances provided by the ATSP with separation responsibility being transferred to the AFR aircraft.

One critical component of any system where control and responsibility is distributed is a set of operating rules that govern the activities of all participants. However, as we move from centralized to distributed roles and responsibilities, changes will be needed to govern and guide interaction between air and ground operators. The distributed control required for a free flight environment requires, among other things, the successful implementation of new 'rules-of-the-road' (ROR) to accompany the new information provided by a CSD and its suite of automation tools.

As participants in a distributed-control environment, the role of the pilot changes. In addition to maintaining responsibility for flying the aircraft, the pilot must now make decisions about the flight plan. For example, pilots will have to ask themselves questions such as "Is my route the most efficient for my aircraft? Is it conflict-free? Is it the best route for meeting the assigned required-time-of-arrival (RTA)?" To aid the pilot, many of these tasks have been automated with the integration of the CSD into the cockpit. Since this new environment is no longer one of "see and avoid" but one of complex, articulated flight paths, the pilot can no longer apply simple flight rules to avoid a conflict situation. Formerly, conflict avoidance was based on the location of the aircraft when the conflict was detected, *not* the location of the aircraft when the conflict may occur. So, a new set of rules, based on the following guidelines were written:

- remove any ambiguity about who is responsible for conflict resolution.
- accommodate more complex route geometries.
- reduce the likelihood of conflicts occurring and encourage a more

organized environment (e.g. pilots abiding by the altitude rule so they reduce the likelihood of being burdened in a conflict).

- if a conflict occurs, allow for a more efficient decision strategy.
- assign responsibility *and* create accountability for conflict resolution.

The CSD rules-of-the-road are listed below and are referenced by the computer automation in the order presented:

- IFR aircraft have the right-of-way when in conflict with AFR aircraft, except when the ATSP has assumed verbal responsibility.

- Aircraft on a flight plan *always* have the right-of-way when in conflict with an aircraft that is off of its flight plan, "on a vector". An aircraft is on a vector when its broadcast flight plan does not include a destination airport

- Altitude Rule: Aircraft have the right-of-way when:

A - Traveling EAST (based on the magnetic compass of 0 - 179 deg) and flying at an ODD altitude level.

B - Traveling WEST (based on the magnetic compass of 180 -359 degrees) and flying at an EVEN altitude level.

An AFR aircraft is burdened if not flying correct direction for altitude. This rule provides natural separation between level east and west bound flights, reducing the possibility of fast closing head-on conflicts between AFR flights.

- Left/Right Rule (when conflict angle is > 20 degrees): Aircraft on the right at the point of conflict has the right-of-way during an encounter between two aircraft when both are level, on ascent, or descent paths.

- Level Flight Rule: Aircraft in level flight have the right-of-way over a climbing or descending aircraft (regardless of heading).

- Descend/Climb Rule: Descending aircraft have the right-of-way over climbing aircraft. The decision to provide priority to the descending aircraft was to aid flight crews arriving into busy terminals to meet ATM arrival constraints.

- Overtake Rule: When the intercept angle between two conflicting aircraft is less than 20 degrees (in other words, they are on the "same" path), the lead aircraft has the right-of-way.

Note: *When none of the rules above apply to the conflict, Ownship assumes responsibility for resolving the conflict. The above rules should cover all possible conflicts, this failsafe rule was added to provide an additional layer of safety. A final failsafe in the system is TCAS.*

Safety of flight takes precedence over all rules.

In addition to the flight rules, the pilots were also assigned specific "roles and responsibilities". Although not embedded in the automation, it was expected they would be followed during the simulation:

- Aircraft ***must*** maintain a minimum separation of 5NM and 1000ft vertical separation from *all* aircraft.
- AFR aircraft ***must*** resolve all conflicts for which they are responsible at least two minutes before LOS. If unable to do so, they were asked to contact the ATSP for assistance.
- AFR aircraft may not create flight plan changes that cause a LOS of less than four minutes.
- The ATSP may verbally assume responsibility for separating an IFR aircraft from an AFR aircraft.
- If the **ATSP** creates a predicted LOS that is within four minutes, the ATSP shall verbally assume responsibility for separating the IFR aircraft from the AFR aircraft.

Although the rules were consistent with those normally used by controllers, they were new to the pilots who informally reported them as cumbersome and difficult to remember. Also, some of the conflict resolution logic may have been counter-intuitive to the pilots who are accustomed to assessing conflict geometry at the time of conflict. Since the rules needed to cover all possible conflict situations that might occur during all phases of flight, reducing the rule set was not an option. And, because it was not the intention of the system designers to turn the pilots into controllers, automating the rule set seemed reasonable.

The automation of the rules relieved the flight crews from the mental and temporal demands of having to assess the right-of-way during a traffic conflict. The knowledge-based system assessed the conflict situation and determined which aircraft was responsible for resolving the conflict. The outcome was a *burden settlement* advisory (Figure 1) to each aircraft involved in the conflict. The burden settlement informs the pilot which aircraft has been burdened with the responsibility to modify their flight trajectory in order to maintain spatial separation (5 NM lateral and 1000 ft vertical) from the conflicting traffic. Each settlement is accompanied by a short phrase, displayed on the CSD, citing the particular rule-of-the-road leading to the settlement advisory. As stated earlier, with the burdening responsibility clearly assigned, it was expected that the crew of the burdened aircraft would take immediate action to resolve the conflict. Pilots were advised not to wait until the LOS window was down to the critical two-minute warning to resolve the conflict for fear that the un-burdened aircraft may feel obligated to resolve the conflict due to the short time to LOS and both resolve simultaneously towards each other. Also, waiting to resolve the conflict could result in a less-optimal solution, increasing the probability that the aircraft, with now limited solutions could resolve by creating a new conflict with another aircraft. If conflicts occurred between multiple aircraft, the burdening logic considered the most eminent conflicting pair by time to LOS, and assigned burdening to one. Once the initial conflict was resolved, the next conflict was considered and a new burdening assignment given. This process continued until all of the potential conflicts were resolved in a timely manner.

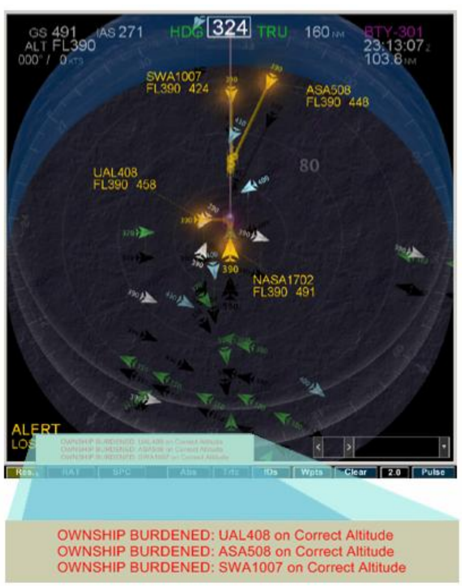

Figure 1. *To remove any ambiguity that may occur when an aircraft is in conflict, the rules clearly assign burdening* responsibility.

Figure 2 shows two AFR aircraft on conflicting routes, one aircraft with an articulated flight path. At the *detection* of the conflict, Ownship is on the right of the conflicting aircraft but at the point of expected LOS, Ownship is on the left and therefore burdened to resolve the conflict. Assessing each conflict situation based on flight path intent and burdening logic does not change over time, or as a function of when the conflict is detected, the rules correctly determine the burdened aircraft at the point of conflict.

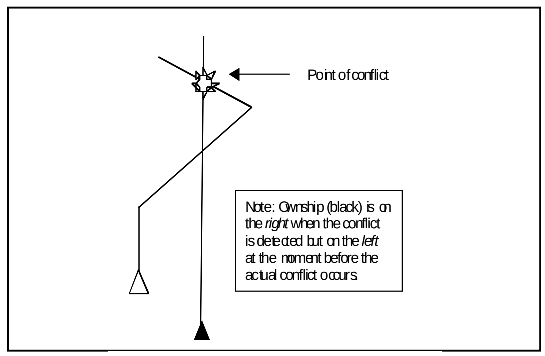

Figure 2. *Example conflict*

Conclusion

After the completion of the simulation, the Ames and Langley pilots participated in separate debrief sessions. The ten Ames pilots were asked in a post-simulation questionnaire, if they thought the rules-of-the-road were “clear and easy to understand”, ninety percent (9/10) of the pilots responded ‘yes’. When asked if they ever had to mentally reference the rules-of-the-road, forty percent (4/10) responded that they had. Noted observations cited the pilots trying to figure out who would be burdened in a potential conflict before the automation responded with a burdening statement.

The pilots were also asked if the rules were adequate for the mixed equipage (IFR and ARF) environment they were presented, seventy percent (7/10) felt the rules were adequate. The pilots also appreciated that it was not necessary for them to remember the rules; when the rules were needed, the automation supplied them. Our data indicates that the crews were able to resolve all conflicts before any loss of separation events were recorded.

Although the CD&R tools allow ample time to resolve conflicts before the four-minute window, it could be problematic if multiple aircraft are maneuvering under the four-minute window or maneuvering and creating conflicts with less than four minutes to LOS. This circumstance could possibly lead to decisions that create additional conflicts of less than four minutes and therefore resolutions that are less than optimal. To resolve this, perhaps rule-based cooperative strategies for resolution of near-term conflict (those under four minutes to LOS) should be explored. It also may be the case that the four-minute window should be expanded to six minutes. Further research is needed to determine which of these solutions is appropriate.

It is also a plus for this application that the burdening solution is unique to the burdened aircraft; only one aircraft needs to respond with a flight change unlike TCAS which requires both aircraft to respond. This reduces the possibility of both aircraft responding in a manner that jeopardizes the safety of flight. It should be noted that there were no case in which both pilots of conflicting aircraft acted to resolve the conflict, and there were no instances of competing maneuvers. These performance results, in a simulated free flight environment, suggest that the aforementioned rules-of-the-road can adequately support self-separation. Maintaining separation requires earlier responses than the current-day collision avoidance tools, and therefore a system such as the one described herein may be necessary to support free flight.

References

Bone, R. Domino, D., Helleberg, J., Johnson, N. (2003). Cockpit display of traffic information (CDTI) enhanced flight rules (CEFR) simulations 1-4. (MITRE Technical Report). McLean, Virginia : MITRE Corporation

Canton, R., Refai, M., Johnson, W. W., Battiste, V. (2005). Development and integration of human-centered conflict display and resolution tools for airborne autonomous operations. Submission to the 2005 International Symposium on Aviation Psychology, Oklahoma City, OK

Granada, S., Dao, A., Wong, D., Johnson, W.W., Battiste, V. (2005). Development and integration of a human-centered volumetric cockpit situational display for distributed air-ground operations. Submission to the 2005 International Symposium on Aviation Psychology, Oklahoma City, OK.

Johnson, W.W., Battiste, V., Granada, S., Johnson, N., Dao, A., Wong, D., Tang, A. (2005). A simulation evaluation of a human-centered approach to flight deck procedures and automation for en-route free maneuvering. Submission to the 2005 International Symposium on Aviation Psychology, Oklahoma City, OK.

Prevot, T., Palmer, E., Smith, N., Callantine, T. (2002). A Multi-Fidelity Simulation Environment for Human-in-the-Loop Studies of Distributed Air Ground Traffic Management. American Institute of Aeronautics and Astronautics Modeling and Simulation Conference and Exhibit, Monterey, CA.

Raytheon ATMSDI Team. (2004). Air traffic management system development and integration (ATMSDI) NASA Joint DAG-TM/CE 5 simulation test plan. Draft document, NASA Ames Research Center, Mountain View, CA.

Radio Technical Commission for Aeronautics (RTCA). (1995b). Free flight implementation (RTCA Task-Force 3 Report). Washington, D.C.: RTCA Inc.

http://www.aerowinx.de/html/tcas.html

http://www.fact-index.com/v/vi/visual_flight_rules.html

http://www.atsb.gov.au/aviation/occurs