Erzberger 2005

Notebook:	UAV Metareasoning Research		
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Author:	Aidan Wallace		

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Notes

- Closely related to the 2007 paper which goes into more detail about the algorithm used
- Algorithm design to meet performance requirements of the Automated Airspace Concept (AAC) further described in 2007 paper
- Based off central computation data sent to aircraft
- Short. Three pages. Lays out the resolution algorithm in simple steps
    1. Conflict Detector (CD) sends conflict pair to resolution generator
    2. Resolution Generator (RG) Provides alternate maneuvers
        1. Determine category of conflict
        2. Determine list of appropriate maneuvers
            - Full list is kept in event of traj. failures and for reference for future conflicts.
        3. Assign priority rankings
            - highest priority minimizes delay or if delay isn't significant, conforms to normal procedures a controller would use
    3. Pass trial resolution to 4D trajectory synthesizer (TS)
        - Uses details of aircraft performance and procedures as well as conditions
        - Two implementations at NASA Ames. CTAS and ACES. ACES was selected.
    4. Pass trial resolution trajectory to Conflict Detector (CD)
    5. If trial resolution trajectory is free of secondary conflicts for resolution time horizon
        - promote trajectory to actual resolution trajectory

       Else:
        - pick next in line trial resolution trajectory
- Maneuvers fall under horizontal, vertical, and speed.
- Paragraph 2: "The algorithm described herein, although formulated specifically to meet the needs of the AAC, provides a generic engine for resolving conflicts. Thus, it can be incorporated into any operational concept that requires a method for automated resolution, including concepts for autonomous air to air resolution.

Summary

Erzeberger posits that automatic conflict resolution is necessary for next-generation air traffic control. He describes an algorithm undergoing trials that will fit the requirements of the Automated Airspace Concept (AAC). Resolution trajectories are generated by a multi-step iterative process involving a RG, TS, and CD. See notes for order of operations.

Review

This paper serves as a precursor to the 2007 paper, basically laying out the same algorithm. Discussion at the end talks of trials underway, but promising results in the scenarios of 3 times current Cleveland Center Airspace traffic density. This is precisely the subject of the 2007 paper.

Erzberger 2007

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Notes

- Possible difference from Erzberger (2005) in all trajectories being calculated and then evaluated vs sequential calculation and evaluation
- Safe separation is 1000 ft vertically or 5nmi horizontally.
- Compare actual air traffic w/ projections from [1] FAA, 2006, *Terminal Area Forecast*, Washington, District of Columbia, USA.
    - Total flight figure for 24 hour period in Cleveland Center Airspace was 7,482 and 3x figure was 24,875
- Read methodology to double and triple flight plans by Paglione [13] and see if they hold up to modern day patterns

Summary

This paper is a continuation of Erzberger (2005) [10] and discusses the results of the presumed trials referenced. The objectives of this paper are to present the requirements put forth by the Automated Airspace Concept (AAC), provide a more in-depth overview of the proposed conflict resolution algorithm, discuss the experimental procedure for testing the algorithm, and present the trial results.

Algorithm

The algorithm is a 'pairwise optimized' approach using the Yang & Kuchar taxonomy. A conflict detection algorithm identifies pairs of aircraft set to lose safe separation (conflicting trajectories) and returns time until loss of separation (tlos), current time (t0), time when separation is lost, and flight plans for both aircraft. This data is also included for downstream conflicts (not the first conflict on traj.). The conflict is categorized based on flight phase, conflict geometry, prior amendments to the flight plan, etc. and is prioritized based off tlos. A Resolution-initiation time horizon (RIH) and a conflict-free time horizon (CFH) are selected based on the categorization. Conflict resolution algorithms tend to operate in the range of 20-2 min RIH, with this algorithm using 8 min for most conflicts. 20 mins is used for aircraft in descent to same arrival fix. CFH=12 min "resulted in acceptable performance" and CFH = 20 min was used for the previously mentioned latter situation. Studies are planned to gain understanding of the trade-offs associated with tweaking these values.

Now the 4D trial-planning loop occurs. The previous categorization and failed 4D trial-plannings are used to navigate a decision tree that determines the selection of maneuvering aircraft and maneuver type. These maneuvers may alter the vertical, lateral, or speed profile of the aircraft, but always return it to a point on its original trajectory. Prioritization occurs based on delay and deviation from nominal trajectory. The 4D-trajectory synthesizer (TS) uses aircraft performance, operational procedures, and atmospheric conditions to generate a trajectory. If this trajectory is free of any further conflicts within the CFH, the trajectory is executed. If not, diagnostics are logged, the trial trajectory is retired, and a new aircraft-maneuver pair is attempted. If no resolution is found after exhausting the options, the algorithm will first defer. This is equivalent to reducing the RIH. A more certain state will possibly make conflict resolution easier, or the conflict will resolve with no action. If tlos=5 min is reached (subject to further analysis), then de-scoping occurs. This is equivalent to reducing the CFH. If the CFH is reduced to 3min, then delegation to a conflict avoidance algorithm occurs. At the time of the paper, this was TSAFE. Conflict avoidance algorithms fit in the space between conflict resolution algorithms and collision avoidance.

Two case studies are used to demonstrate the application of this algorithm. Important aspects of a double arrival conflict (a more complex and common issue in busy airspaces like Cleveland) are compliance with arrival-fix crossing restrictions and preserving the assigned arrival sequence. Also important to note, in this case study, de-scoping is used to solve the primary conflict. Then, to solve the secondary conflict, certain maneuvers were not considered since they were previously determined to not resolve the primary conflict.

Review

The authors' motivations in their test-plan was to develop benchmarks for how any algorithm performs based on the "2x to 3x" traffic demands of the AAC (this was projected to occur for 2020 according to reference [1]. The Cleveland Air Route Traffic Control Center (ARTCC) was chosen for the experiment. Cleveland airspace and flight operations were simulated in the Airspace Concept Evaluation System (ACES). A 24 hour period with no human controller intervention was simulated in 1x, 2x, and 3x traffic scenarios. It is important to note that the results exclude arrival-vs-arrival conflicts because of test bed shortcomings. There was no uncertainty in trajectory model, so a separation requirement of an additional 2nmi was implemented. The safety results of the algorithm are quite impressive, showing more than 99% resolution without deferring, de-scoping, or delegating for all traffic levels. Also, most of the delegated conflicts were detected at RIH < 2min, which is below the threshold for delegation set by the system architects. Although not validated, this paper claims that post-simulation analysis shows that for all conflicts delegated to TSAFE, the conflict resolution algorithm would have been sufficient. It is also important to note that in higher traffic scenarios, an increased portion of conflicts were detected at tlos < 2 min. This is because the simulation environment does not support airspace handoff procedures. Omission of these "late" detections gives even more impressive safety results. As for efficiency, the results demonstrate an average delay of no more that 25 seconds for all traffic levels. In the highest traffic scenario, only 4% of conflicts required a delay of > 2 min. Delay spread increased with increased traffic demands, but the delay is directly correlated to the number of iterations . This reinforces the idea that the algorithm prioritizes the most efficient maneuvers first.

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Erzberger 2010

Author: Aidan Wallace

Summary

This paper outlines the conflict avoidance algorithm referred to in Erzberger (2007) as TSAFE (tactical separation assured flight environment). Conflict avoidance is a necessary component in the requirements posed by the Automated Airspace Concept (AAC). Conflict avoidance fills the niche between conflict resolution and collision avoidance. This is typically in the time-span of 30 sec<tlos<2 min. Only horizontal maneuvers are considered in the scope of this paper.

The Maneuver

Let turn angle = heading change. First, equations for the turn angular velocity w.r.t. the bank angle and velocity are given, along with the x and y velocities w.r.t. the turn angle. Airspeed is assumed to be held fixed. This assumption, along with limiting the maneuvers to the horizontal plane, makes each trajectory under consideration a circular arc followed by a line segment. Therefore, there is no need to solve any differential equations. These maneuvers are also very familiar to a pilot and easy to fly.

Turn radii w.r.t. velocity and bank angle are determined for conflicting aircraft A and B. A maneuver is defined by turn direction, bank angle, and length of time. In the case of a cooperative solution, both aircraft will turn at the same bank angle for the same time interval.

To determine position vectors during the turn segment of a maneuver, vector algebra and the initial coordinates/headings of both aircraft are used along with the aircrafts' calculated turn radii and current turn angles. Determining the position vector if the aircraft does not turn is trivial. The position vectors are taken w.r.t. aircraft A's initial position.

Separation between aircraft when executing the turn portion is determined by the absolute value of the position vector difference. It is also important to note that the absolute value of the turn angle ratio is inversely proportional to the velocity ratio of the two aircraft.

The next step is determining minimum separation in the straight line portion of the maneuver. This is sufficient due to the fact that lines intersect at only one point. Minimum separation and time-after-turn of minimum separation are approached on the condition that at minimum separation, the position difference vector and relative velocity vector of the two aircraft must be perpendicular. This is represented by a zero dot product. An equation can be found for the time of minimum straight line separation by plugging in variable representations of these vectors into the dot product. This time can be plugged back into the separation vector equation for the straight line segment to find minimum straight-line separation.

Four theorems are put forth to demonstrate how initial conditions (speed of aircraft A and position, heading, and speed of aircraft b) determine minimum separation that can be achieved. Eight subsets of maneuvers are determined by turn/inaction combination alone. On top of this, heading change angle and set bank angles are explored.

The Four Theorems are As Follows (Proofs on page 230)

1. In positive-slope intervals of the minimum turn separation vs. resolution angle function, minimum turn separation equals minimum separation overall.
2. In negative-slope intervals of the same function, minimum turn separation is greater than minimum separation overall.
3. At extremum, minimum turn separation is minimum separation overall.
4. Minimum separation is always less than or equal to minimum turn separation.

NOTE: There appear to be inconsistencies in what exactly the turn locus of the plots should be representing. The author in the theorems refers to it as minimum turn separation, but it is labelled as separation at the end of turn in Fig. 3. I am inclined to think that all theorems and plots should be for separation at end of turn rather than minimum separation during the turn, since intuitively, a **minimum** separation during the turn is not a differentiable function of turn angle (it will reach a constant value after closest flyby) nor is it cyclical. The explanation of the theorems also make more sense this way. Algorithm tables also show a singular minimum turn distance which supports my assertion.

Composite graphs <u>separation distance</u> and <u>time</u> vs. aircraft turn angle(s) are generated for a range of bank angles. This gives a convenient graphical representation for all possible maneuvers and shows their safety/efficiency. Four graphs must be generated to cover all combinations of maneuver (left/right + straight, straight + left/right, left/right + right, left/right + left). Generating these graphs for a number of different scenarios have allowed unique scenario properties to be cataloged and implemented into the resolution algorithm.

Algorithm

The end result is an aural advisory to the pilot(s) to make a heading change in a certain direction at a standard or expedited turn rate. 15 and 30 degrees were chosen for these rates, respectively.

A separation buffer is incorporated into the algorithm to allow for variability in exact turn rate from the pilot(s).

1. The algorithm searches for a single-craft solution. If multiple succeed, then one with least heading change is selected.
2. If unsuccessful, algorithm will do same thing, but for expedited turn rates.
3. If unsuccessful, algorithm searches cooperative maneuvers at expedited turn rates.
4. If unsuccessful, the algorithm selects the cooperative maneuver that maximizes minimum separation regardless of if separation maintains "safe" guidelines (5nmi).

<u>Detailed:</u>

1. Calculate minimum turn separation and corresponding turn angle for a specified bank angle and direction. If turn separation is sufficient, a solution is known to exist with less turn angle that hits exact separation requirements. (Result of theorems)
2. Find required turn angle for this solution using equations of the maneuver detailed in previous section.
    1. Calculate min straight line separation (dsmin)using small increments of turn angle
        1. If dsmin is initially decreasing, all turn angles from zero to the minimum are disqualified because they result in less separation than the null maneuver. (Thm 2)
        2. If turn angle for first minimum is the minimum turn separation angle, then this turn direction does not have an acceptable solution.
        3. Otherwise, angles are incremented until a max is reached. Max will always be found at angle less than or equal to min turn angle.
            1. If former, compare dsmin max with required separation.
                1. If max >= required, then a solution angle is known to exist somewhere in there. This is solved by standard iterative procedures for non-linear equations.
                2. If max <required, no solution exists in angle range between min and max. If required separation <= minimum turn separation, then an acceptable solution lies at min turn angle.
                3. Otherwise, no safe solution for maneuver under consideration.
3. Resolution maneuvers that minimize heading change are optimal and referred to as type 1. However, these may cause an unreasonable resolution time. This occurs when straight line segments become nearly parallel. Therefore, if time to turn to angle for required separation in straight line exceeds time to reach minimum turn separation by a certain percentage (20%), then the minimum turn separation angle is substituted if separation is still safe. This is referred to as type 1a.
4. The 12 maneuver types are then ranked. Ones that achieve separation are placed at the top and labelled successful.
5. Maneuver types are placed into tables by standard angle, high angle, and cooperative high angle.
    - Sub-tables typically have more than one successful maneuver. Redundancy can be used to satisfy additional constraints like close-by aircraft and inability to maneuver.
    - Sub-table rows specify maneuver type and parameters.
    - First listed solution is typically type 1 (minimizes heading change) but can be 1a.
6. If tables are exhausted of legal maneuvers, the algorithm goes into a two-step soln. strategy.
    1. Select from cooperative sub-table the maneuver that maximizes minimum separation.
    2. Select an end-of-turn heading that is greater than minimum turn angle. This corresponds to turn angle that achieves required separation. This is type 2a.
    3. If no turn angle > minimum turn angle is found such that required separation is achieved while turning up to and including the angle that gives maximum turn

separation, the turn is terminated at the angle where turn separation is maximum. This is type 2b.

See Figures 5 (p.235) and Tables 1 and 2 (p.237) to ease the inevitable confusion induced by that wordy explanation

7. Before resolution can be accepted, near-term conflicts must be considered.
    1. If candidate trajectory causes conflict with other nearby a/c determined by a chosen time parameter (3 min). This is done with same separation eqns. as previous section, and same trajectory parameters are taken (min turn separation, min separation, etc.) This uses orthogonal frame of reference w.r.t. the maneuvering a/c.
    2. If conflict exists, check for opposite turn direction first.
    3. If conflict still exists, repeat checking available turn directions for the other a/c.
    4. Continue onto higher bank angles if conflict still exists.
    5. If previous failure, vertical maneuvers may be necessary or an increase resolution turn angles beyond values in Table 1.
    6. Final option is to maximize minimum separation within specified time horizon.

Review

The time horizon proposed for the implementation of this algorithm (2 min) is motivated by the fact that at short distances, an aircraft's fixed turn radius must be a primary consideration in achieving safe separation. An algorithm that iteratively calculates trajectories by applying turn dynamics to idealized ones (like Paelli [6]) becomes too cumbersome when turn dynamics dominate the time-span of the maneuver. Thus, not relying on a trajectory engine was the goal. This algorithm is called TSAFE and is intended to function as the conflict avoidance feature in the automated airspace concept (AAC).

This algorithm relies on a much more specified maneuver type than Erzberger's previous papers on conflict resolution. Qualitatively this maneuver can be described as a semicircle followed by a straight line. This is because conflict avoidance occurs in a much shorter time-span and therefore must rely on more shortcuts. Limitation of maneuver selections to turn maneuvers at standard bank angles also expedites the process and has the added benefit of routine familiarity to the pilot.

The language used to describe the separation locus plots became slightly burdensome to my understanding of the core characteristics that the plots reveal about the maneuver. Also, the chronological order by which the algorithm processes and flags different maneuvers became unclear, the primary example being when maneuvers were getting assigned their respective types. Nonetheless, the use of the plots and theorems to demonstrate properties of the maneuver that are not immediately apparent, and how said properties can be leveraged in decision-making proved to be quite elegant.

The paper briefly discusses weighting of heading change vs. time in turn in situations when these can be selected as a trade-off. For an algorithm that seems to be so intent on determining the optimal solution, I was surprised to see that no further calculation for the trade-off was made other than a simple time-to-execute barrier. I can only assume that this is because at such close range, priority is put upon achieving a safe minimum separation as fast as possible, especially due to the presence of other traffic likely to cause conflicts. Another decision that I can only attribute to expediency was the consideration of only high bank angles for the cooperative maneuvers. This is likely because they are tested last and time to conflict has substantially decreased. Therefore, jumping straight to the more drastic maneuvers increases likelihood of success.

The author specifically notes (p.234) intention for implementation in a ground-based system, but that air-to-air avoidance with the same algorithm is possible.