A Modeling Methodology for Manned and Unmanned Aircraft in a Close Airspace Environment

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ABSTRACT

This methodology is developed during an investigation into the airspace management requirements for integrating manned and unmanned aircraft operations in a close airspace environment. One of the by-products of this research was an Airspace Simulation Program (ASP). This spreadsheet-based program attempts to model the flight paths of multiple aircraft within a designated airspace environment and then calculate the distance between them at any given time. This allows the user to determine the minimum distance encountered between aircraft while operating in the airspace. The simulation relies on key user inputs to establish boundary conditions: airspace radius, airspace entry locations for each aircraft, time interval between aircraft entries, and initial aircraft headings, altitudes, and airspeeds. The simulation then allows each aircraft to randomly vary airspeed, altitude, and heading for each time interval and calculates the aircraft's position for each. It further calculates the distance between the two aircraft at each time interval and returns the minimum distance encountered during the flight to the user. Finally, the program conducts a probabilistic analysis through Monte Carlo simulation. This analysis allows the user to determine airspace safety by calculating the probability that aircraft come within a specified distance of each other. With further development and utilization, airspace simulation could become the standard by which the safety of military, commercial, and civil aviation operations is measured.

INTRODUCTION[*]*

Aviation experts will undoubtedly agree that the 21st Century will see the continued growth of the aviation industry on a global scale. The research and development of Unmanned Aerial Vehicles (UAV), Personal Air Vehicles, as well as the investigation into the feasibility of commercial space travel illustrate how the 1940's science fiction world of Isaac Asimov is becoming or is already the reality of today. The development and integration of these technologies in addition to the eventual recovery of commercial and general aviation from 9/11, combined with the FAA's National Airspace Modernization Plan illustrate a trend for increasing the number of aircraft flying overhead.[1] However, as the events of 2001 so effectively illustrated, as congestion in the sky increases, so must the emphasis on safe airspace management.

The same is true in military aviation operations. The development and incorporation of the UAV as a force multiplier is forcing a paradigm shift in the employment of military aircraft. This is especially true when it comes to US Army Aviation, consisting primarily of rotorcraft operating in limited airspace within 1000-ft of the ground. The integration of UAVs into this airspace significantly increases the potential for accidents when compared to those operating at higher altitudes. However, given the Army's airspace limitations and the incorporation of UAVs into the three-dimensional battlefield, little has been accomplished for ensuring the safety of personnel on the ground and Army aviators in the air. One of the primary considerations lacking is a quantifiable measure of airspace safety, a tool for military commanders to determine safe, marginal, and unsafe levels of airspace saturation. Before any extensive integration of manned and unmanned aerial vehicles can take place, a safe and reliable airspace management system must be firmly established with established procedures, equipment, etc. Airspace simulations such as the one proposed here are a vital component to establishing the required system architecture.

BACKGROUND

In 2001, while referring to the success of UAVs supporting Operation *Enduring Freedom* in Afghanistan, President George W. Bush stated that UAVs were "re-writing the rules with every day that

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[*] *Presented at the American Helicopter Society 59th Annual Forum, Phoenix, Arizona, May 6-8, 2003.*

passes in the Afghan conflict." He further acknowledged that the DOD would increasingly rely on autonomous vehicles in the execution of military operations.[2] The Army's Aviation Applied Technology Directorate (AATD) provides the testbed for incorporating airborne autonomous systems into the Objective Force. However, in a presentation to the Army Science Board, AATD identified airspace management as one of the critical barriers to the successful integration of manned and unmanned aircraft.[3] Therefore, a separate investigation was launched to analyze the airspace management requirements and propose a system capable of safely managing manned and unmanned aerial vehicles.

The investigation provided an integrated approach to airspace management through the use of a formalized methodology for determining system requirements, generating design alternatives, and evaluating each against a structured evaluation criterion. One of the analyses that made this approach particularly unique was an extensive safety analysis conducted using a Safety By Design process endorsed by the FAA for the certification of airborne systems.[4] The end result of that analysis was the quantification of the probability of system failure of the design alternatives under consideration.

However, the limitation of this analysis was that it defined system failure as the inability to effectively manage the selected airspace. It did not consider the most catastrophic form of system failure: the collision of two or more aircraft. Historical data confirms that a majority of aircraft collisions occur in congested airspace: airports, military training areas, etc., precisely the environment created by combined manned and unmanned aircraft operations. Therefore, the need arose to investigate this condition and model it in terms of probability. The result was airspace simulation; the tool developed was the Airspace Simulation Program (ASP).

METHODOLOGY

The Airspace Simulation Program is a MS-Excel® spreadsheet-based program designed to quantify the probability of aircraft collision within a given section of airspace. It accomplishes this by modeling the random flight paths of two aircraft within a designated airspace environment at any given time. It then calculates the aircraft positions at each time interval and the distance between the two. The simulation can then determine the minimum distance encountered between aircraft for a given operation. Through Monte Carlo simulation, the program is repeated over several thousand iterations in order to generate a probability distribution.

The simulation requires key user inputs to establish boundary conditions: airspace radius, airspace entry locations for each aircraft (θ), time interval between aircraft entries (Δt), and initial aircraft headings (ψ), altitudes (h), and airspeeds (V). These boundary values represent the initial conditions of each aircraft at the moment in time that each enters the airspace. The time interval is divided into 120 sequential steps; each interval corresponds to one minute. The simulation assumes that the aircraft remain within the confines of the airspace for a two-hour operation.

The program begins with the entry of the first aircraft into the airspace. The program randomly varies the altitude, heading, and airspeed of that aircraft and calculates the resulting position for each time interval. To ensure that these parameters remain within reasonable limits, a series of checks is performed. If still within limits, the random values are used in calculating aircraft position. If outside accepted limits, default values are then substituted for the out-of-tolerance variables to determine the aircraft's position.

Once position is calculated, the program performs one last check that ensures each aircraft is still within the airspace segment. If so, the simulation advances to the next time step, and the entire process is repeated. If not, the aircraft heading is automatically set toward the center of the airspace circle before advancing to the next time step. The second aircraft follows the same calculation process, based upon the time it enters the airspace. The flow chart presented in Figure 1 illustrates this methodology.

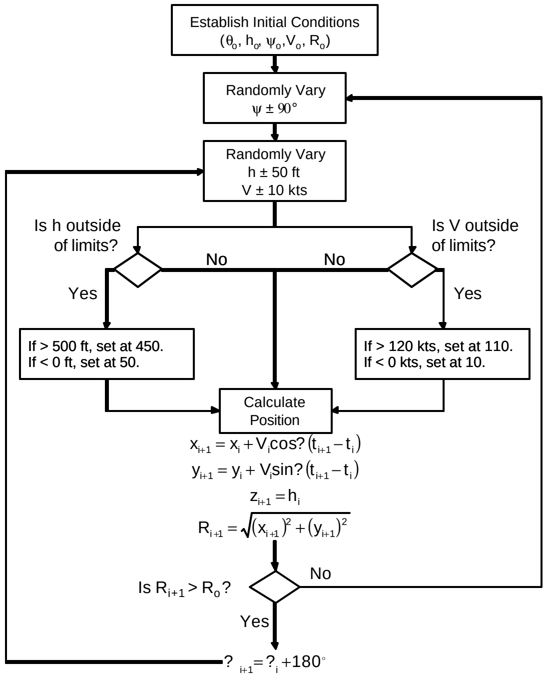


Figure 1: ASP Position Calculation Algorithm

The program completes the position calculation for both aircraft and determines the straight-line distance between them at each time interval. Finally, the algorithm determines the minimum distance encountered between the two aircraft over the 120-min operation and returns that value to the user as seen in Figure 2.

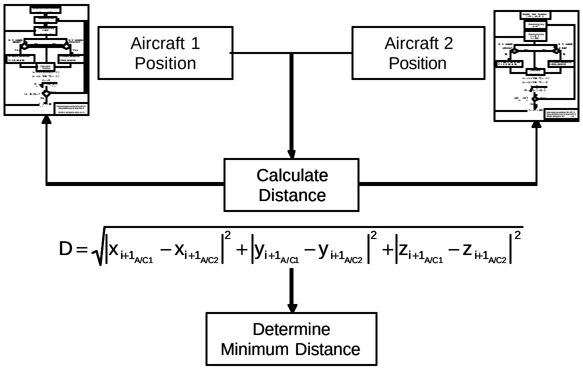


Figure 2: ASP Distance Calculation Algorithm

The final step in the simulation generates the uncertainty model as illustrated in Figure 3. This is accomplished by assigning probability distributions to the boundary conditions and performing a Monte Carlo simulation over 10,000 iterations. The minimum distance encountered between aircraft during the flight is identified for each iteration and plotted in a frequency diagram. The frequency diagram will yield a probability distribution, giving the user a quantifiable measure of the probability of aircraft collision. These results can provide the user with the probability that multiple aircraft will come within a specified distance of each other.

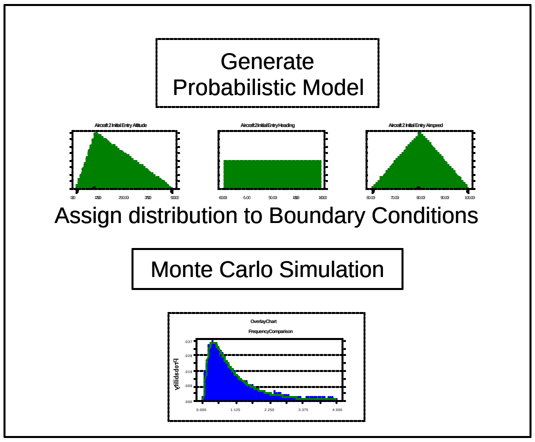


Figure 3: ASP Probabilistic Methodology

A two-dimensional graphical depiction of this methodology follows in Figure 4. It depicts a circular section of airspace of radius, R_o, and shows two aircraft entering the airspace at a specified time interval. Each aircraft varies its heading, altitude and airspeed between each time step, represented by the points, (x_1, y_1), (x_2, y_2), etc. The program then calculates the distance between the aircraft for each step, represented by the dotted lines. The figure also shows that if an aircraft leaves the airspace, such as at (x_3, y_3), the aircraft will automatically adjust its heading toward the center of the airspace circle.

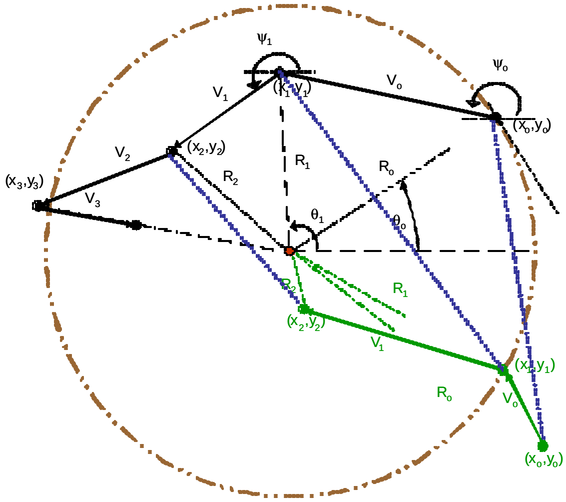


Figure 4: ASP Graphical Representation

SIMULATION MODELS

A collision results from two factors: aircraft occupying the same three-dimensional space at the same time. For purposes of the ASP, aircraft were represented as a single point in space, although they are obviously not points and do have sizable dimensions and mass.

An additional goal of the simulation study was to identify multiple scenarios in an attempt to model different types of operations or the effects of certain types of controls on the probabilistic outcome. Initially, three scenarios were identified. All three continued to utilize random flight patterns throughout the airspace. The purpose fo random flight paths was to encompass several conceivable aircraft profiles during one operation: aircraft flying to different landing sites or varying altitude throughout a flight pattern to simulate terrain flight, evasive maneuvers, obstacle clearance, etc. The only differences between the three were the points at which the aircraft entered the airspace. The objective of these scenarios was to analyze the effects of certain imposed control methods on aircraft safety. The first scenario was identified as Random Entry – Random Flight Path (RE-RFP). The second and third scenarios were variants of the same titled Controlled Entry – Random Flight Path (CE-RFP) and are referred to as CE-RFPs 1 and 2, respectively. Table 1 illustrates the differences between the three scenarios.

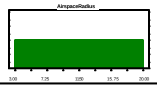
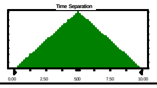
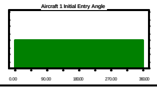
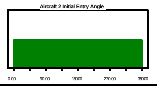
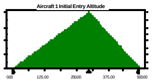
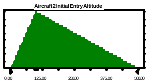
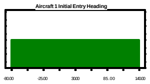
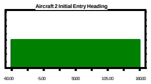
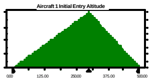
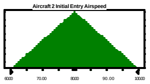
Table 1: Scenario Descriptions

Scenario	**Airspace Entry Limitations**
RE-RFP	None. Both aircraft can enter from any angle.
CE-RFP1	A/C 2 enters within 45° either side of A/C 1's entry location.
CE-RFP2	A/C 2 enters 90° out based upon A/C 1's quadrant of entry
	A/C 1 enters NE quad; A/C 2 enters NW quad.
	A/C 1 enters SE quad; A/C 2 enters SW quad.
	A/C 1 enters SW quad; A/C 2 enters SE quad.
	A/C 1 enters NW quad; A/C 2 enters NE quad.

It is important to note that these scenarios were just an attempt to model certain controls that one might expect to see during a military operation, i.e., aircraft entering the objective airspace from very nearly the same direction (±45°), or the same general hemisphere (same side of the map).

For each model, the boundary condition parameters were assigned the distributions presented in Table 2. However, in the CE-RFP scenarios, the A/C 2 Entry Angle parameter was dependent upon that of A/C 1. Notice that the distributions were all uniform or triangular in nature.

Table 2: Boundary Condition Distributions

Airspace Radius (nm)	Time Separation (min)
	
A/C 1 Entry Angle (deg)	A/C 2 Entry Angle (deg)
	
A/C 1 Entry Altitude (ft)	A/C 2 Entry Altitude (ft)
	
A/C 1 Entry Heading (deg)	A/C 2 Entry Heading (deg)
	
A/C 1 Entry Airspeed (kts)	A/C 2 Entry Airspeed (kts)
	

Scenario 1: (RE-RFP). The first scenario consisted of both aircraft entering the airspace from any angle and flying a random flight path for the duration of the operation. Using the boundary conditions of Table 2, the Monte Carlo simulation was run using Crystal Ball® software, recording the minimum distance between aircraft over 10,000 iterations. All distances greater than five nautical miles were filtered out, resulting in the frequency diagram of Table 3. A probability distribution was then fitted to the diagram with the results also presented in Table 3.

Table 3: Scenario 1 Model Results

RE-RFP

Lognormal Distribution

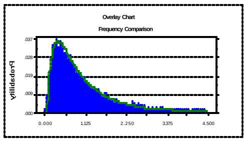
Mean = 1.267 nm

Std Dev = 1.471 nm

95% Confidence Band

(0.127, 4.251 nm)

50% chance of aircraft coming within 0.842 nm of each other



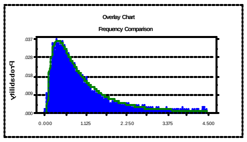
Scenario 2: (CE-RFP1). Recall that the second scenario forced the second aircraft to enter within ±45° of the first aircraft's point of entry. This scenario eliminated the randomness of the second aircraft's entry. Since in military operations, aircraft routes and flight paths are seldom, if ever, picked at random, this scenario models the aircraft entering the airspace from a common direction. The same boundary conditions were applied; the only difference was the limitation

placed on the second aircraft's entry point. The simulation provided the results outlined in Table 4.

Table 4: Scenario 2 Model Results

CE-RFP 1
Lognormal Distribution
Mean = 1.260 nm
Std Dev = 1.514 nm
95% Confidence Band
(0.121, 4.353 nm)

50% chance of aircraft coming within 0.824 nm of each other

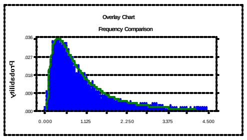


Scenario 3: (CE-RFP2). The third scenario was the final attempt at modeling control methods. This scenario examined the effects of two aircraft entering from the same hemisphere of the airspace circle, but different quadrants, as described previously in Table 1. The results of this scenario are presented in Table 5.

Table 5: Scenario 3 Model Results

CE-RFP 2
Lognormal Distribution
Mean = 1.286 nm
Std Dev = 1.514 nm
95% Confidence Band
(0.124, 4.34 nm)

50% chance of aircraft coming within 0.841 nm of each other



The objective of the two controlled-entry scenarios was to see if those two particular control methods had any appreciable effect on extending the distances encountered between the two aircraft. What the results show is that the minimum distance encountered by the aircraft was almost completely insensitive to their points of entry.

More importantly, the scenarios all concluded that there was a 0.0% chance of aircraft collision, although there was a slight possibility (2.5%) that the aircraft would come uncomfortably close (within 1000-ft) of each other.

AN EXAMPLE OF RANDOMNESS

The following figure (Figure 5) illustrates the randomness of the flight and is intended only to depict how the ASP simulates flight patterns over the course of the two-hour operation. The figure is equivalent to viewing the airspace from above, as if looking at a map. The circle depicts the boundary of the airspace, with the lines illustrating the flight patterns of the aircraft. One will notice at the boundaries how the aircraft return to the confines of the airspace by turning toward the center of the circle, one of the checks incorporated by the system. It is important to note that the scale of the chart is in feet, so while it may look like some of the flight paths extend abnormally outside the airspace perimeter, most do not reach more than half of one nautical mile outside the airspace before turning around.

Another note is that while the aircraft paths are intersecting at multiple points, the two-dimensional nature of this chart fails to include the altitude of the two aircraft and the time at each position.

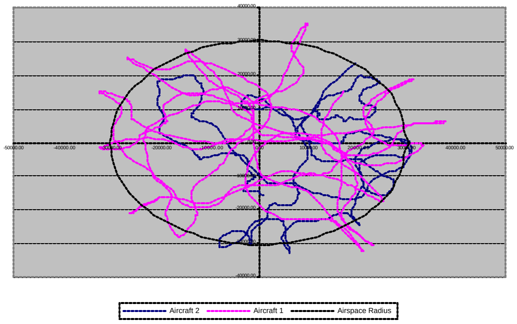


Figure 5: Illustrating a Random Flight Path

LIMITATIONS AND PLANNED IMPROVEMENTS

As with every mathematical model, there are limits to the ASP's application. Its current generic form only simulates two aircraft and only for a 120-minute operation of random flight patterns. The random flight path scenarios are beneficial in that they illustrate that two aircraft operating randomly in a segment of airspace have a negligible chance of colliding, although they may come within an unsafe distance of each other. Ultimately, however, for a simulation to be useful for military or commercial applications, it has to model aircraft conditions as realistically as possible, to include non-random effects: air traffic control, designated flight routes, collision avoidance systems, etc.

Planned improvements include but are not limited to the following five objectives.

1. Adding the capability for simulating more than two aircraft under non-random flight conditions.

2. The incorporation of methods to simulate Air Traffic Control, Collision Avoidance Systems, etc.

3. Varying the duration of mission operations to effectively simulate different types of operations.

4. Reducing the time intervals of one minute to twenty-seconds or smaller. The smaller the interval, the more distances calculated to provide more credibility that the minimum distance reported during an iteration would actually be the minimum distance encountered.

5. Rather than varying the airspace radius as one of the boundary conditions, conducting the simulation for fixed airspace dimensions (i.e., 1-nm, 5-nm, 10-nm, 20-nm, etc.) to provide a more credible safety level for a particular sized airspace of interest.

These improvements will most likely force a transition from spreadsheet-based algorithms to computer-code calculations. However, the result would provide a realistic, credible method of determining varying degrees of airspace safety.

CONCLUSION

In concluding, the rapidly expanding applications and utilization of aviation in the 21st Century, especially with respect to the evolution and technological maturity of autonomous flight systems, will ultimately require a focus into the safety and development of airspace management procedures to accommodate the growing air traffic congestion. Airspace simulation is a first step in providing a robust method of quantitatively determining safe, marginal, and unsafe airspace levels of saturation. Its applicability is ideal for those aviation operations in constrained airspace environments: Army Aviation and airport operations.

The ASP models the flight paths of two aircraft operating within a given segment of airspace and measures airspace safety by determining the probability of aircraft collision or intrusion of one by the other. While the scenarios revealed that the probability of two aircraft colliding is negligible, the aircraft in some instances could come close enough to each other to create possible unsafe conditions.

Although the ASP is currently in a generic form, further improvements could significantly increase its realism and credibility. In a truly advanced military application, airspace simulation could allow Army aviation pilots and UAV operators to simulate manned and unmanned missions prior to ever leaving the ground. Accounting for flight routes, possible enemy action, mechanical failure, etc., the ASP could assess the risk of integrated manned and unmanned operations in addition to that associated with multi-aircraft operations in general. This could provide the user with a means of determining the maximum number of aircraft that could safely be operated within the given airspace. This would provide the military commander with the ideal means for evaluating and then accepting or rejecting risk.

Finally, airspace simulation could be applied to all sectors of aviation: military, commercial, or civil applications where airspace constraints or air traffic congestion pose a recurring problem.

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