Quantifying the Effects of Uncertainty in a Decentralized Model of the National Airspace System

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ABSTRACT

The modernization of the National Air Traffic Control System is on the horizon, and with it, the possible introduction of autonomous air vehicles into the national airspace. Per the FAA Aerospace Forecast (FAA, 2013), U.S. carrier passenger traffic is expected to average 2.2 percent growth per year over the next 20 years with government statistics indicating that the average domestic load factor for airlines in 2014 was approximately 84.4 percent (US Department of Transportation, 2015). Adding to that demand, the potential introduction of unmanned and autonomous air vehicles motivates reconsideration of control schemes. One of the proposed solutions (Eby, 1994) would involve a decentralized control protocol. Equipping each aircraft with the information necessary to navigate safely through integrated airspace becomes an information sharing problem: how much information about other aircraft is required for a pilot to safely fly the gamut of a heavily populated airspace and what paradigm shifts may be necessary to safely and efficiently utilize available airspace? This thesis describes the development of a tool for testing alternative traffic management systems, centralized or decentralized, in the presence of uncertainty.

Applying a computational fluid dynamics-inspired approach to the problem creates a simulation tool to model both the movement of traffic within the airspace and also allows study of the effects of interactions between vehicles. By incorporating a Smoothed Particle Hydrodynamics (SPH) based model, discrete “particle” aircraft each carry a set of unique deterministic and stochastic properties. With this model, aircraft interaction can be studied to better understand how variations in the nondeterministic properties of the system affect its overall efficiency and safety. The tool is structured to be sufficiently flexible as to allow incorporation of different collision detection and avoidance rules for aircraft traffic management.
Dedication

I dedicate this work to my family for their patience, love, and support. Brook, Addison, and Cade, thank you for helping me keep life in perspective. I love you.
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List of Abbreviations

- CDF – Cumulative Distribution Function
- CFD – Computational Fluid Dynamics
- CD&R – Conflict Detection and Resolution
- CP -- Conflict Prevention
- ECEF -- Earth-Centered, Earth-Fixed
- FAA – Federal Aviation Administration
- GPS – Global Positioning System
- LOS – Loss of Separation
- NAS – National Airspace System
- NED -- North/East/Down
- PDF – Probability Distribution Function
- SPH – Smoothed Particle Hydrodynamics
- UAS – Unmanned Aerial System
- UAV – Unmanned Aerial Vehicle
- VHF – Very High Frequency
- VOR – VHF Omnidirectional Radio Range
Chapter 1 - Introduction

1.1 Motivation

The volume of sky available for aircraft utilization is immense and inefficiently used. The implementation of NextGen by the FAA (FAA, 2014) has jumpstarted a slew of research in an attempt to determine the path forward to handling air traffic management within the National Airspace System (NAS). Can the current centralized management scheme handle the projected increase in air traffic over the next decades? Can a decentralized methodology maintain aircraft separation and overall safety with a record as good or better than the record of current air traffic management? Is some method of cooperation between centralized and decentralized management schemes the answer?

There exists a growing amount of research attempting to answer some of these questions to one degree or another, many of which will be discussed within the following section of this thesis. The purpose of this research is to create a tool designed to assist the analysis of an often chaotic and unpredictable system. While it was necessary to develop a separation assurance and resolution function for the testing of this simulation tool, the methodology and the tool’s characterization of nondeterministic and stochastic aspects of the airspace system are fairly novel qualities.

1.2 Literature Review

The subject of traffic dynamics is not new. Scientists and mathematicians have been applying physics to study traffic flow in vehicular traffic as well as in large groups of pedestrians, flocks, and herds as early as the 1930s (Greenshields, 1935). By the 1950s, it was evident that traffic density in urban areas was increasing more rapidly than the highway infrastructure being built to support the additional traffic, so attempts to characterize and understand traffic models increased in earnest (Helbing, 2001) in an effort to mitigate the added congestion. This congestion was primarily responsible for the creation of the Interstate highway system in the 1950s (“Interstate,” 2015).
One of the earliest macroscopic traffic models created as a result of increased traffic awareness is called the Lighthill-Whitham model (Lighthill, 1956). The model assumes a restriction that on/off ramps and accidents are discounted for simplicity. The assumption that the total number of vehicles on the highway remains constant leads to the continuity equation

\[ \frac{\partial \rho(x,t)}{\partial t} + \frac{\partial Q(x,t)}{\partial x} = 0 \]  

(1)

where \( \rho \) is the traffic density, and \( Q(x,t) \) is the traffic flow per lane, a product of the traffic density multiplied by the average vehicle velocity. This equation states that the change in traffic density over time is equal to the change in traffic flow per lane over the roadway. By solving this partial differential equation, characteristics of large traffic systems such as kinematic wave propagation, shock fronts, and transitions from a low-density state to a high-density state can be better understood. In laymen’s terminology, these terms represent phenomena such as stop-and-go traffic, “phantom” traffic jams that have no evident cause, and roadway maximum capacity.

The traffic density on our nation’s highways has only increased since concern over traffic congestion was first suggested, as evidenced by the highways in and around large cities like Atlanta, Los Angeles, and Washington DC where main thoroughfares become parking lots at rush hour. As traffic density increases, a dangerous and costly consequence is a rise in vehicular collisions (USDOT, 2015). Studying the dynamics of traffic is a way to reduce and minimize the cost and casualties from collisions.

The work done in vehicular traffic dynamics has laid the groundwork for application to aeronautical transportation. As with ground-based traffic, air travel has increased significantly since the formation of the first commercial airlines. Per the FAA Aerospace Forecast (FAA, 2013), U.S. carrier passenger traffic is expected to average 2.2 percent growth per year over the next 20 years with government statistics indicating that the average domestic load factor for airlines in 2014 was approximately 84.4 percent (US Department of Transportation, 2015). Passenger load factor measures the capability of airlines to effectively fill their seats. The technology, policies, and paradigms of early air travel have been strained in recent decades to keep up with the increased passenger loads. While society became increasingly technologically savvy in the late twentieth and early
twenty-first centuries, the aviation industry in large part was unable to keep up with the evolution of technology.

Without the aid of satellites, pilots historically have used a variety of techniques to route to a destination. Some of the historic navigation aids discussed in this survey include “dead reckoning,” LORAN, and airway/beacon systems, and precision/non-precision approaches.

In navigation, the term dead reckoning (or “ded reckoning” which is short for deduced) refers to the use of a previously determined position and estimations of speed, direction, and elapsed time to calculate a current position. Since speed, general direction, and elapsed time are typically estimated for these calculations, dead reckoning is subject to a great deal of error and uncertainty.

Long range navigation (LORAN) was a system which utilized hyperbolic navigation, or the “difference in timing between the reception of two signals, without reference to a common clock.” (LORAN, 2015). The differences in timing allowed a calculation of distance to a receiver. LORAN was first developed in the United States during World War II to aid the Navy in the Atlantic Ocean and within the Pacific theatre of WWII. The system was used by aircraft as well as ships. Due to expense and near-exclusively military use of the LORAN system along with the popularity and accuracy offered by GPS, LORAN began phasing out of use in the 1980s. The signal was officially terminated in 2010.

Another method of navigation used by pilots is a system of airman’s maps and beacons which lay out a map of pre-defined airways to ensure position (Figure 1). When the pilot flies out of range of one beacon signal, he/she picks up the next beacon signal and changes heading to coincide with a defined airway. Very High Frequency (VHF) Omni Directional Radio Range (VOR) is an example of a non-precision instrument approach procedure that utilizes these beacon and roadmap systems for navigation. The beacon/airway method ensures that pilots flying in bad weather or in areas with little or no identifying landmarks avoid getting lost, and the airway system helps air traffic controllers deal with traffic management and aircraft separation. By restricting air traffic from three dimensional space to airways along a single dimension, creating highways in the sky, air traffic controllers are able to deconflict potential collision scenarios along
these vastly simplified routes. While beneficial to humans trying to resolve potential conflicts, this system also creates very inefficient flight paths with angles and frequent turns. The introduction of satellite-based navigation aids enable the use of more efficient flight paths without the need for radio beacons, visual landmarks, and predefined airways. Although more aircraft are becoming equipped with GPS, air traffic controllers continue to rely on the airway system as a means of maintaining aircraft separation (Eby, 1994). As a result of increased use of GPS on aircraft, many American airway beacons have been decommissioned (Figure 2).

Figure 1: Map of US Airway Beacons. Used with permission of Jennifer Galas (Galas, 2015)
Figure 2: Remnants of Transcontinental Air Mail Route Beacon 37A, located in St. George, Utah. Used with permission of Wikipedia.

In an effort to upgrade outdated technology in airports and on airplanes and to mitigate high air traffic density in and around large metropolitan airports, the Federal Aviation Administration (FAA) has begun implementing Next Generation Air Transportation System (NextGen) concepts and technologies. NextGen improvements are aimed at “enhancing safety, reducing delays, saving fuel, and reducing aircraft exhaust emissions” (FAA, 2014). NextGen timelines have generated an abundance of research in the air transportation industry in recent years, particularly in efforts to improve flight path efficiency and in the automation of collision avoidance systems.

Once navigation within the NAS is viewed as a 4D (three spatial dimensions plus time) problem, it becomes a conflict detection and resolution (CD&R) problem that requires the use of computers, decentralization of control authority, or both (Eby, 1994) due to the complexity of the problem. A conflict in the world of aviation is a predicted loss of separation between two aircraft. A great deal of research has gone into writing computer algorithms that maintain aircraft separation requirements. Various classes of CD&R functions are identified based on a few distinctive capabilities: the model’s
dimensions, detection capabilities, conflict resolution techniques, maneuver dimensions, and multiple conflict capabilities.

The state information for CD&R algorithms may include horizontal plane information only, vertical plane information only, or both horizontal and vertical plane information. The model may or may not have explicitly defined aircraft detection capabilities; this is a way of differentiating models with conflict versus non-conflict definitions from models that identify conflicts based on proximity. There are various categories of conflict resolution techniques that further characterize a model including prescribed, optimized, force field, manual, and no resolution. Prescribed resolution follows a set of predefined rules for avoidance, optimized resolution attempts to maximize flightpath efficiency (Bilimoria et al, 2000), force field methods repel/attract other simulated objects such as other aircraft and airports (Eby, 1994), some models allow the user to manually resolve conflicts, and some models emphasize the detection of conflict without resolution. If maneuvers are performed, various dimensions of maneuvers may be allowed (i.e. horizontal or vertical maneuvers, speed changes, or some combination of the three). Another distinction that can be made among conflict resolution techniques involves the final trajectory of the aircraft. Strategic conflict resolution involves a trajectory change that returns the aircraft to its final destination, while tactical resolution will resolve conflict without incorporating the aircraft destination or flight plan (Spitzer, et al., 2015). Another distinction that can be made regarding various CD&R functions is its capability to handle multiple conflicts. If the ability to examine multiple conflicts within the airspace exists, distinctions are typically made between methodologies which allow pairwise or global resolution (Kuchar & Yang, 2000).

The Autonomous Operations Planner (AOP) is a prototype flight-deck research system that works in conjunction with automated self-separation of aircraft (Karr, et al. 2012). Developed by NASA, AOP handles information about the aircraft on which it is installed and manages flight trajectory. If necessary, AOP provides advisories to the crew regarding trajectory changes and has additional capabilities in some cases to provide recommended modified trajectories to aircraft systems for execution (Spitzer, et al. 2015).
Some collision avoidance systems are fail-safe methods that are intended to prevent collisions after other separation assurance methods have failed. The traffic collision avoidance system (TCAS) currently used in many commercial airliners to reduce the incidences of mid-air collisions is one such system currently used in the NAS. MIT Lincoln Laboratory has also been working on a new approach as a potential replacement/update for TCAS. The Airborne Collision Avoidance System X (ACAS X) utilizes Markov decision processes (MDP) to determine states probabilistically (Kochenderfer et al., 2012). Markov decision processes are a mathematical framework in which decisions are shared between randomized methodology and “decision maker” policy. Automated control is one of many areas in which MDP is widely used.

Automating collision avoidance measures, also called separation functions, reduces the burden on air traffic towers and pilots to a certain extent. However, these functions must take into account stochastic characteristics of the system being characterized. Human factors, such as pilot delay and variation in response time from one pilot to another, weather, and mechanism failure are nondeterministic aspects of the NAS that contribute greatly to its uncertainty. A recent study (Consiglio et al., 2008) performed at NASA Langley Research Center assessed the impact of pilot delay in terms of loss of separation and number of conflicts created. A simulated pilot with varying response times responded to warning indicators from automated separation functions when the presence of a converging aircraft in the vicinity necessitated a heading change. The simulated pilot’s response time was varied from 5 to 240 seconds with a small percentage of randomly selected pilots programmed to completely miss the conflict alerts and therefore take no action. Results of the study on this particular airborne separation system revealed that the system can sustain pilot response delays of up to 90 seconds, depending on traffic density but that a lack of response from the operator or pilot results in increased occurrences of conflict and considerable safety issues.

In an effort to generate an effective CD&R function with the ability to study uncertainty and nondeterministic properties of the NAS, such as human factors and mechanism failure, this research borrows methodology from the realm of computational fluid dynamics (CFD). Most CFD approaches involve generating meshes over some amount of fluid to isolate small sections and numerically solve complicated governing
equations for the fluid region. Smoothed Particle Hydrodynamics, however, is a discretized approach in which each fluid particle possesses its own material properties and moves according to the conservation equations. SPH was first invented to solve nuclear fission problems in astrophysics (Lucy, 1977) and has since been used in various other applications: hydrodynamics, shock simulations, fracture of brittle solids, high velocity impacts, heat transfer, and mass flow (Liu & Liu, 2003). The mechanics of this method will be discussed in more detail within the Methodology section of this thesis.

1.2 Thesis Objective

This research focused on the creation of a simulation tool with the purpose of studying the nondeterministic and stochastic aspects of the NAS. The possible inclusion of unmanned aerial systems (UAS) into the NAS along with the anticipated rise in air traffic in following years has led to increased interest in the incorporation of a decentralized control protocol. Can a decentralized management scheme handle the dynamic and chaotic nature of deconflicting aircraft trajectories? This simulation tool and the research contained within this thesis seek to aid in answering this question. While a methodology for routing air traffic and handling multiple aircraft interaction is proposed via SPH, the tool is intended to be used in conjunction with other CD&R functions to test their effectiveness (in terms of separation assurance) in a system full of uncertainty and chaotic influences.
Chapter 2 – Simulation Tool

2.1 Methodology

Within the computational fluid dynamics (CFD) community, there is a subset of researchers focused upon the use of particle-based methods for simulating fluid flows. As detailed in Liu and Liu (2003), mesh-free particle methods address a host of problem scales and types, from microscopic to astronomical, and deterministic to probabilistic. Specific traits of the smoothed particle hydrodynamics (SPH) methodology include discretization of a domain (if it is not already discrete) into particles with individual sets of properties; in the fluid dynamics context this would be characteristics such as mass, velocity, density, and pressure. Due to this discretized nature and ability to handle interactions of particles with dramatically different properties, this thesis is focused upon development of a simulation tool, philosophically grounded in the SPH approach, to model behaviors of dramatically different types of vehicles and pilot skill sets operating in the NAS. By incorporating a smoothed particle hydrodynamics based model, discrete “particle” aircraft each carry a set of unique deterministic and stochastic properties, such as manned/unmanned, reaction time, weight, maneuverability, failure mechanisms and rates, etc. (Figure 3)

Figure 3: Illustration of analogue between SPH modeling and air traffic modeling using an SPH-like method. Used with permission of Dr. Leigh McCue.
A key operation within SPH is the use of a smoothing (or kernel) function for particle property approximation. A smoothing length is defined for each particle that identifies a support radius for identifying interacting particles, and the kernel function approximates particle properties via a weighted average of the particle properties within the support radius. A variety of kernel functions have been used successfully within the SPH community. In Lucy’s 1977 use of SPH for fission, the following kernel function was used (Lucy, 1977):

\[
W = \alpha_d \times \begin{cases} 
(1 + 3R)(1 - R)^3 & R \leq 1 \\
0 & R > 1 
\end{cases}
\]

where \( W \) is the smoothing function, \( \alpha_d \) is \( \frac{105}{(16\pi h^3)} \) (for 3D space) or \( \frac{5}{(2\pi h^2)} \) (for 2D space), and \( R \) is the distance between particles divided by the smoothing length, \( h \). Figure 4 illustrates the relationship between particles’ relative distance and the effect that distance has on their interaction based on a bell-shaped smoothing function. The y axis shows indicates a peak in values when the distance between two particles is zero. This particular function is well-suited to this project due to our definitions of aircraft interaction and support radius. A support radius is defined for each aircraft; outside this radius, aircraft need little, if any, information about surrounding traffic, so the kernel function should be zero beyond \( R \) equal to one.

This distance-dependent smoothing function is then used to create a “particle approximation.” Any function of a particle can be approximated in SPH by essentially averaging the values of that function among all particles within the smoothing length and weighting the average with the smoothing function. When SPH is applied to the NAS, the interactions of aircraft will be estimated through the use of a smoothing kernel.
function to arrive at a modeling tool for multi-aircraft interactions. The tool is capable of modeling a virtually unlimited (bounded only by computational constraints) number of craft with flight envelope information specific to twenty-one types of aircraft. Within the tool, the smoothing length from SPH methodology is analogous to an aircraft awareness radius. Each aircraft/pilot must have some knowledge of its surroundings, which has the capability to be chosen based on aircraft size, speed, and maneuverability. Additionally, the amount of information required from each surrounding aircraft will vary with distance; in the realm of fluid dynamics, the closer a fluid particle is to its “interaction pairs,” the more influence that particle exerts on its neighbors’ properties. Similarly, within the simulation tool, the smaller the distance separating interacting aircraft is, the more each aircraft’s characteristics/properties influence collision avoidance trajectories.

In the event of a single “interaction pair” identification, the avoidance measure is simply determined based on the Right-of-Way Rules for aircraft, following directions for approaching head-on, converging, overtaking, and yielding according to aircraft class. In this event the application of SPH methodology is likewise straightforward. The kernel approximation used to estimate the properties of particles based on the distance that separates them is applied to the aircraft’s avoidance trajectory or heading angle. If the field of interacting particles is a single pair, only the interacting aircraft will influence trajectories. If, however, the field contains 2 or more interacting aircraft within a single awareness radius, evasive maneuvers must be commanded based on some weighted average of proximity. This hierarchy must be created based on proximity, closing distance, maneuverability, and traditional rules of the air.

2.2 The Model

The earth frame is defined in Earth-Centered, Earth-Fixed (ECEF) coordinates. The body frame is expressed in North/East/Down (NED) coordinates. The transformation matrix from ECEF to NED frame within the code for each aircraft is

\[
\begin{bmatrix}
-sin(\phi)cos(\lambda) & sin(\phi)sin(\lambda) & cos(\phi) \\
 sin(\lambda) & cos(\lambda) & 0 \\
 cos(\phi)cos(\lambda) & cos(\phi)sin(\lambda) & sin(\phi)
\end{bmatrix}
\]  

(3)
where $\phi$ is latitude and $\lambda$ is longitude. This matrix is well-documented and included in Matlab’s utilities.

Aircraft are initialized with a pseudo-randomly generated origin and destination within the simulated airspace, and are assigned a trajectory following a great circle route to the destination. Great circle routes can be calculated with either the haversine formula or the spherical law of cosines. Due to Matlab’s capability to handle 16 significant digits of precision, the coding simplicity of the spherical law of cosines is preferable to the haversine formula and produces results with the same accuracy. Therefore the simulation uses spherical law of cosines to calculate distance along the great circle route from Point A to Point B, and is given as:

$$d = a \cos(\sin \varphi_1 \sin \varphi_2 + \cos \varphi_1 \cos \varphi_2 \cos \Delta \lambda) * R$$

where $R$ is earth’s radius. The horizontal flight path angle is given as

$$a \cos\left(\frac{\sin \varphi_2 - (\sin \varphi_1 \cos(d))}{\cos \varphi_1 \sin(d)}\right)$$

If two aircraft come within 10 nautical miles horizontally and 300 meters vertically of each other, the aircraft are then commanded to follow evasive actions based on their respective positions. The “governing equations” of the simulation tool are modeled after the Right of Way rules for aircraft (Gleim, 2006). These rules determine which aircraft yields in a potential collision scenario. For aircraft approaching each other head-on, or nearly so, each aircraft alters course to the right. Overtaking aircraft must alter course to the right and pass well clear of the aircraft being overtaken. For converging aircraft, the rules for right-of-way are based on aircraft class, with more maneuverable classes of aircraft yielding to the less maneuverable, otherwise same-class aircraft yield to whichever aircraft is on the other’s right side. Once two aircraft are calculated to be within 10 nautical miles of each other and 300 meters or less vertically, a series of comparisons of the aircraft heading angles are made to determine how the aircraft will yield. A sample algorithm for head-on collisions is coded as follows:

```plaintext
if abs(HFFPA(time,1)-HFFPA(time,2)) <= 180 + 5 &&
    abs(HFFPA(time,1)-HFFPA(time,2)) >= (180 - 5)
    HFFPAc(1) = HFFPA(time,1) + turn;
    turn(1) = 1.0;
elseif ...
```
The above algorithm looks at the two aircraft interacting and compares the horizontal flight path angle (HFPA) for aircraft 1 and 2 at the given time step. If the difference in heading angle is calculated to be between 175 and 185 degrees (indicating a head-on scenario), aircraft 1 will turn and a flag will toggle ‘on’ noting that the aircraft has maneuvered. The ‘turn’ flag will remain turned ‘on’ until the aircraft is outside the other’s awareness radius at which point, the ‘turn’ flag will toggle to ‘off.’ Preliminary simulation results show two aircraft avoiding collision in Figure 5 where the encounter is marked by a pink ‘+’ at each time step. The two simulated aircraft are flying the same great circle route, in opposite directions at different speeds intentionally programmed to collide. Once collision has been avoided and both aircraft are outside the other’s awareness radius, the simulation calculates a final course alteration to arrive at the intended destination, modeling a strategic resolution.

Figure 5: Simulation output showing two aircraft diverting to avoid collision

Figure 6: Zones of interaction for multiple aircraft 1) head-on, 2) converging, 3) overtaking

The simulation is intended to model traffic within a heavily populated airspace. As traffic density increases, so too does the complexity of the conflict avoidance algorithms. Figure 6 is intended to illustrate a potential scenario with multiple aircraft interacting within a single awareness radius. The vehicle in the center will represent the
aircraft of interest. The zones for following 1) head-on collision, 2) converging aircraft, and 3) overtaking aircraft rules are labeled. In this particular example, an aircraft of similar class is approaching head on, another similar-class aircraft is converging to the right of the aircraft of interest, a much larger jet is overtaking the aircraft of interest, and a hot air balloon is in an area of convergence on the left of the aircraft of interest. Each of these scenarios separately would generate a different course alteration for the aircraft of interest. In the first case, two aircraft at similar altitudes in a head-on (or near head-on) collision trajectory must both turn to the right. For cases of similar class aircraft converging, the one to the other’s right has right-of-way, so the aircraft of interest must yield. The jumbo jet overtaking the aircraft of interest must pass on the right, and although the hot air balloon is on the left of the aircraft of interest, that class of craft has right-of-way in nearly all encounters. The combination of these four potential conflict scenarios creates a very complicated conflict-avoidance problem for the aircraft of interest, particularly in a 2D model. While SPH provides a tool to weight each interacting aircraft by proximity and vary the trajectory of the aircraft of interest accordingly, the extent to which this method provides a tool for multi-aircraft interaction remains largely untested. Within the current tool, incorporation of the SPH methodology is in place via definition of an awareness radius (10 nautical miles horizontally), and the kernel function in Equation 2 is currently programmed to assign the full “weight” of trajectory calculation to the nearest interacting aircraft, where the kernel function, \( W = 1 \). The programming architecture for Equation 2 exists within the tool and should be explored further to investigate its ability to handle multi-aircraft interaction.

2.2.1 Aircraft Types

An important feature within the simulation tool is its ability to characterize specific aircraft. The tool has information stored for twenty-one various aircraft with the demographic intended to represent each class of aircraft from planes to gliders (Table 1). The list is made up of more airplanes, particularly of the large commercial transport variety, than any other aircraft class. Characterization is primarily based on altitude and speed envelopes to ensure that the elevation and speed of an aircraft is an accurate representation of its flight capabilities (Appendix A-1).
2.2.2 Aircraft Speed Distributions

A subset of this research is an attempt to identify the distribution of speeds for a given type of aircraft within the NAS in order to properly model that distribution within the simulation tool. Websites like flightaware.com (FlightAware, 2014) give aircraft type, location, and speed information for aircraft currently flying worldwide, with the ability to select areas within the NAS. Data from these websites was compiled in an effort to fit the speed distributions and determine if a uniform or normal speed distribution is more appropriate. The majority of data points obtained for the aircraft characterized within the simulation tool numbered 25, but 50 data points were obtained for the Airbus A320 (See
Appendix A-2). For this reason, the Airbus A320 data was utilized to determine the distribution of aircraft speed.

A cumulative distribution function (CDF) was generated based on 50 samples. The CDF for a normal distribution is recognizable based on its low probability distribution at the extreme values of the variable and a more steeply-sloped curve where a higher concentration of variable values exists. This is representative of the normal, or Gaussian, bell curve (when viewed as a probability distribution function). The CDF for a uniform distribution has a constant, positive slope. The CDF for the speed data obtained from flightaware.com (FlightAware, 2014) for the Airbus A320 (Figure 7) is inconclusive for purposes of determining if the distribution is normal or uniform.

![Figure 7: CDF for Airbus A320 speed distribution data. The distribution function matches neither a uniform nor a normal distribution.](image)

Additional testing of the data involved looking at the distribution of the speed data itself to see if the number of aircraft flying at a particular range of speed is constant or if it resembles the bell curve. Again, the illustration in Figure 8 is inconclusive. A plot of Airbus A320 altitude vs. speed was generated to see if there might be any correlation with this data (i.e. aircraft speed increasing with altitude), but again, there was no correlation observed (Figure 9). The ambiguity in correlating speed to altitude is likely
due to the ground speed reported by FlightAware. Winds at altitude can be significant, as much as 100 or more knots, and drastically affect the measured ground speed.

Figure 8: Speed Distribution for Airbus A320. Distributions do not strongly resemble either a uniform or a normal distribution across the range of speeds.

Figure 9: Airbus A320 Altitude vs. Speed. There is no visible correlation between altitude and speed.

The inconclusive results of all the previous classification attempts leave the decision of how to model aircraft speed and velocity non-deterministically within the simulation tool unjustified. A decision to assume these properties are distributed uniformly within each aircraft’s operating envelope was made. Therefore, within the aircraft characterization files of the simulation tool, the nondeterministic generation of
these property values for uncertainty quantification will utilize Matlab’s ‘rand’ function. If future research indicates a normal distribution is more appropriate, the only edits necessary to the tool would be to change the ‘rand’ command to ‘randn’ and include some basic information about the mean and standard deviation of the distribution.

2.2.3 Output

Simulation output (Figure 10) shows aircraft trajectory over the course of simulated time. Each trajectory is color-coded based on aircraft class shown in the legend, with aircraft in distress marked with a red ‘o’ and aircraft that have lost separation in a given time step with a red ‘x.’ A loss of separation between two or more aircraft is defined as any horizontal distance less than five nautical miles with a vertical distance less than 300 meters. This separation is intended to prevent aircraft from colliding as well as prevent accidents due to turbulent wakes (Gleim, 2006). Within this simulation tool, the trajectory initialization is not constrained by airspace separation standards, so it is possible that two or more aircraft could be generated within the loss of separation radius of another aircraft. For this reason, 60 seconds is given at the onset of a run for aircraft to maneuver away from each other before LOS is formally recorded. The example shown in Figure 10 demonstrates a scenario in which two incidents of separation loss (in the upper right and lower left quadrants) are shown between two airplanes. A single LOS is counted if two or more interacting aircraft lose separation. The LOS is also only counted once if the LOS between two more aircraft continues for multiple time steps.
The geographic area represented in simulation output is one degree of latitude by one degree of longitude. For reference the location of these latitude and longitude coordinates is in central Illinois and encompasses 69 x 57 standard miles horizontally, and approximately 3.3 miles vertically. However, the output from the simulation tool is not necessarily intended to represent typical air traffic within these coordinates. The trajectories within the code are generated pseudo-randomly without information regarding typical airway routes or increased traffic near airports. For the purposes of this research, the density per square mile is of more importance than the representation of airport or airway traffic. This is a high-level model of airspace modeling aircraft that are in their cruise phase of flight.

Chapter 3: Results

3.1 Sample Size

Chapter 3 contains data accumulated in an effort to determine the boundaries of the simulation tool. The parameters of interest (typically aircraft velocity, altitude,
trajectory/position, etc.) within the system are considered nondeterministic parameters due to the influence of uncertainty on their values. For example, wind plays a factor in determining aircraft velocity, trajectory, and altitude and will always cause some amount of uncertainty in their quantities. For this reason, non-deterministic variables along with their uncertainty can be modeled by Monte Carlo sampling. In order to reduce confusion, the following terminology will be used to define the sampling terminology. A simulation is a single case with ‘x’ aircraft and some number of variables modeled non-deterministically. A sample size is the number of simulations with the non-deterministic parameters allowed to vary upon which statistics are generated. A sample size of 10 means that the tool is exercised 10 times with non-deterministic parameters varied with each sample based on a pseudo-randomly generated uniform distribution. A nested run is a loop of samples. Within this section, 25, 50, and 100 Monte Carlo samples were taken. Then three nested runs were compared for each value of sample size to determine robustness of the result.

The simulation tool has the current capability to model five variables non-deterministically, aircraft velocity, altitude, origin, destination, and demographic (aircraft type). Without varying the structure of the aircraft characterization files, the minimum number of parameters that can be represented non-deterministically is two: velocity and altitude. In order to demonstrate that Monte Carlo sampling numbers are sufficient, the simulation was run three times with the minimum number of nondeterministic parameters for each sample size: 25, 50, and 100. For each nested run, the cumulative distribution functions (CDF) of the variable of interest (number of separation losses) were compared for these three runs. If the CDF for each run is near the same or identical, then a sufficient number of samples can be assumed (Oberkampf & Roy, 2010).

For initial determination of the sample size, velocity and altitude parameters were varied non-deterministically assuming a uniform distribution over the flight envelope, while each aircraft’s origin, destination, and demographic remained constant. An illustration of the flight trajectories generated for this test can be seen in Figure 11. A population of 100 aircraft was selected for this test.
Figure 11: Simulation output showing trajectories for 100 aircraft of varying class. Output shows one LOS in lower left quadrant.

The CDF data for the three nested 25-sample runs (Figure 12) indicates a 100% probability that the tested scenario, with velocity and altitude varied in each run, will produce four or fewer separation losses. The probability of LOS within each of the three 25-sample Monte Carlo runs varies quite a bit. The CDF data for the three 50-sample runs (Figure 13) indicates a 100% probability that the tested scenario will produce seven or fewer separation losses. The CDF data for 100 samples (Figure 14) indicates a 100% probability that the tested scenario will produce six or fewer separation losses. The data for the sets of 50 and 100 Monte Carlo runs show very similar results.
Figure 12: CDF output for three 25-sample runs (some results may overlay). The probability of 4 or fewer incidents of LOS is 100%. There is some disagreement between sets of data.
Figure 13: CDF output for three 50-sample runs (results may overlay). The probability of 7 or fewer separation losses is 100% for the particular set of trajectories run. There is small disagreement between three runs.
Figure 14: CDF output for three 100-sample runs. The probability of 6 or fewer separation losses is 100% for the particular set of trajectories run. There is some small disagreement between runs.

Based on the agreement between 50 and 100 samples for this test case, 50 samples appears to be a sufficient number of samples to characterize uncertainty in the velocity and altitude of each aircraft in a given airspace distribution.

In order to test the population density boundaries of the simulation, it was necessary to determine the number of samples suitable for varying not only altitude and velocity but trajectory as well. A natural byproduct of increasing the number of aircraft over Monte Carlo runs is that the trajectories within the system change. Therefore, it is imperative to model trajectory as a non-deterministic quantity in additional tests. This will determine the sample size for estimating the population capacity of the simulation tool.

As in the previous test, velocity and altitude were varied non-deterministically at every sample (25/50/100) and for every nested run (1, 2, and 3). Unlike the previous test, there is no single figure that describes the trajectory used for this test. The trajectory was
allowed to change for every Monte Carlo sample, modeling the quantity nondeterministically. The number of aircraft used was 100.

The CDF data for the three 25-sample runs (Figure 15) indicates some disagreement between the two sets of data. One data set indicates a <5% probability that no LOS will occur, another set shows a 16% probability that no LOS will occur, while the last set of data indicates a 24% probability that no LOS will occur. The probabilities of 2 or more conflicts are fairly similar among the three sets of data.

Figure 15: CDF output for three 25-sample runs. With a population of 100 aircraft, these results indicate varying degrees of disagreement between the three nested runs.
Figure 16: CDF output for three 50-sample runs. With a population of 100 aircraft, these results indicate a 100% probability that there will be 6 or fewer separation losses.
Figure 17: CDF output for three 100 sample runs. With a population of 100 aircraft, these results indicate a 100% probability that there will be 6 or fewer separation losses.

The CDF data for the 50- and 100-sample runs (Figures 16 & 17) shows very little variance between the two sets of results. An approximate 20% probability exists that a scenario will produce one or zero separation losses and there is an approximate 10% probability of four or more separation losses occurring. The CDF data for 50 samples (Figure 17) indicates close agreement between the two data sets, showing a 50% probability that one or fewer conflicts will occur and less than a 20% probability that three or more conflicts will occur.

Based on the comparison of CDF data from 25, 50, and 100 samples, 50 samples was determined to be a sufficient number of samples to characterize uncertainty in the velocity, altitude, and trajectory of each aircraft within the aircraft density boundary test.

3.2 Simulation Tool Bounds

With a sufficient sample size selected, the uncertainty of some of the simulation parameters of interest was investigated in an effort to document the boundaries and
capabilities of the simulation tool as a baseline for future users. Two parameters of interest tested were population density of aircraft within a given area and the capability of a given portion of airspace to handle stochastic events.

To test the boundaries of the simulation in terms of population capacity, ten nested runs of 50 samples each were produced. The initial population size tested was 50 aircraft, and at the onset of each subsequent nested run, the aircraft population was increased by 50 for each case to a final population of 500. Results from this test are included in Figure 18. The average LOS count for a given case is marked by an ‘x’ and the error bars represent one standard deviation. The nondeterministic quantities varied for each simulation in this test were aircraft velocity, altitude, and trajectory. A visual of the simulated airspace with 500 aircraft can be viewed in Figure 19.

Results from population density test revealed expected trends. An anticipated behavior in most CD&R algorithm output is to see an increase in the LOS count as the density of the aircraft population increases. Simulation output in Figure 18 shows a very low LOS count when the aircraft population is below 100. On the other end of the spectrum, at very high densities, a drastic increase in the number of separation losses can be seen. The number of separation losses as a percentage of total population remains fairly constant at about 2% until around 400 aircraft when the percentage begins to increase to 3% by 500 aircraft.
Figure 18: Results from 10 cases of 50 samples each. With each case, population was increased by 50 aircraft. As population density increases, so does the number of separation losses.
Figure 19: Simulation output with 500 aircraft and 6 separation losses.

Because the altitude distribution could not be justified based on FlightAware data accumulated (A-1), it was important to investigate the differences utilizing a normal distribution of aircraft over the vertical simulated space generate in simulation output. For this reason, the aircraft characterization files were slightly altered to reflect a normal distribution of each aircraft type over the simulated altitude. In theory, this will tend to concentrate more aircraft at the typical cruise altitudes for each aircraft type (Figure 20). Due to this concentration of aircraft close to the mean altitude for cruise flight, the incidents of LOS should increase. Figure 21 shows results from this comparison, and the average number of separation losses increases for a normal (green) distribution of aircraft over altitude.
Figure 20: Illustration of uniform (left) and normal (right) aircraft distribution over altitude.

Figure 21: Loss of separation as a function of aircraft population. Normal distribution of aircraft over altitude generates more LOS.

To test the boundaries of the simulation in terms of stochastic event capacity, the distress or emergency class assignment was initiated at randomly assigned times to randomly assigned aircraft. This class re-assignment places the aircraft in distress at the
top of the maneuvering hierarchy, so all other aircraft classes will maneuver around the aircraft in distress. Eleven cases of 50 samples each were produced. The population of aircraft used for this test was 50 with zero aircraft declaring emergency initially. At the start of each subsequent case, the population of aircraft in distress was increased by 5 to a final population in distress of 50 (meaning all aircraft have signaled distress at some point during the simulation). All aircraft were placed between 2000 and 3000 ft to give the scenarios a more dense vertical space and will consequently result in more conflicts even though the total number of aircraft simulated is lower for this particular test. The nondeterministic quantities varied for each simulation in this test were aircraft velocity, altitude, and trajectory. Results from this test are included in Figure 22.

![Figure 22: Simulation Results showing the average number of separation losses for increasing numbers of aircraft in distress. Results indicate that the conflict resolution function is in fact decreasing the number of separation losses in a given scenario.](image)

Anticipated results from the stochastic event capacity tests should reveal very little change in the LOS count initially. The conflict resolution function within the simulation tool commands maneuvers based on aircraft class, with aircraft in distress
given right-of-way in all circumstances. The data would be expected to reveal a threshold at which the number of aircraft in distress, and therefore not maneuvering, generate more conflict with each other. The data in Figure 2 reveals expected trends for relatively low numbers of distressed aircraft in the system. The average number of separation losses is approximately 7 with similar standard deviations until the simulation reaches 15+ distressed aircraft. Results then indicate a gradual increase in the LOS count to a final average count of approximately 9. This trend indicates that the conflict resolution function is in fact decreasing the average number of collisions in a given scenario.
Chapter 4 – Discussion

While some of the very effective, existing CD&R algorithms, such as the “Voltage Potential Algorithm” (Eby, 1994) are better able to handle large population densities, it should be noted that the aim of this particular work is to develop an efficient simulation tool capable of modeling nondeterministic features for use in comparing alternate CD&R schemes. Eby’s (1994) Voltage Potential Algorithm by its nature resists LOS, at the expense of flight path efficiency. Other methodologies, such as those behind TCAS and ACAS X (Kochenderfer, 2012) have a high success rate as well. This tool allows one to experiment with different conflict resolution schema and compare to a baseline, “rules of the road”-type structure.

The simulation tool in its current state deals with multiple aircraft interaction in a rudimentary fashion, by prioritizing the interacting aircraft and maneuvering to avoid the closest. However, the methodology coded into this CD&R function has an untapped potential for dealing with aircraft maneuvers that determine trajectory based on a weighted urgency from interacting aircraft. Rather than make two separate maneuvers to avoid two interacting aircraft, an aircraft of interest need only make a single maneuver to avoid them both.

This tool has the capability to simulate very dense portions of airspace. It should be noted that the aircraft densities discussed within the Results section of this thesis are more dense than typical 2015 airspace traffic within the NAS with reasonably small computational expense. These density observations come from comparison to densities modeled in other CD&R research. For example, in a publication comparing centralized and decentralized traffic management model capabilities (Krozel, 2001), the traffic densities discussed range from approximately 1.5 to 25 aircraft per 10,000 square nautical mile. Additional supporting evidence comes from monitoring flightaware.com (FlightAware, 2014) and selecting airspace view over particular areas of the NAS. Observing traffic over locations outside of large metropolitan airports like Chicago O’Hare International, the density is typically more like 10-50 aircraft per 10,000 square nautical miles, depending on proximity to a major airport hub. It is noted that
FlightAware does not include all aircraft types and classes within the selected airspace, only those flying on an Instrument Flight Rules (IFR) flight plan. The horizontal size of the airspace modeled within this simulation tool is approximately 2760 square nautical miles, and tests were conducted in the hundreds of aircraft (Figure 23). The vertical space simulated in these tests is 3.3 miles or the equivalent of eight aircraft’s vertical separation distance high. Computation time for a simulation of 100 aircraft to fly one hour takes 1-2 minutes depending on how many maneuvers are necessary for the population.

![500 Aircraft Simulation](image)

**Figure 23:** Sample simulation output demonstrating the size of simulated space in nautical miles. Depending on the Latitude, Longitude ranges from 45 - 56 nautical miles.

The test data obtained in this research revealed that an estimated 10% of separation losses were due to multiple aircraft interaction. Simulation output revealed that an aircraft maneuvering to avoid an interacting aircraft, is unable to maneuver away from a second interacting aircraft. These are the types of LOS that the SPH methodology has the potential to avoid, but due to the rudimentary application of the kernel function, the current simulation tool does not resolve these conflicts. Fully implementing the SPH methodology and using multiple interactions to determine maneuver is likely to decrease
the LOS count by at least 10% with an aircraft population of 100 in the simulated frame of airspace. The remaining separation breaches require further analysis, but more rigorous algorithm analysis of aircraft trajectories and closing velocities will certainly decrease LOS occurrence as well.

Further characterization can be added to the aircraft data to enhance the simulation tool. The current aircraft characterization files contain information about the aircraft’s minimum and maximum operating altitudes and speeds. Additional information such as emergency turn rates would increase the fidelity of the model, and having the ability to more accurately model distress or emergency behavior adds an interesting dimension of the stochastic nature of the system to the problem.
Chapter 5 – Conclusions

5.1 Usage

This tool is of direct use to researchers studying NextGen technologies and decentralized control schemes. There are many on-going studies estimating the safety and efficiency of various collision avoidance algorithms. Studies to maximize efficiency in conflict resolution (Figure 24) will benefit from analyzing stochastic variations in the scenarios of interest. The tool is a test bed for probabilistic simulation probing separation assurance and testing classification schemes, validating novel communications tools and assessing human-systems interaction when using ground control station operations, and serving as a platform for integrated testing and evaluation. For purposes of this research, most importantly, it serves as a means toward studying canonical cases to qualitatively and quantitatively understand the influence of various sources of uncertainty in a decentralized future model for air traffic control with emphasis on planned technologies under development by NASA and/or encompassing aspects of the NextGen air traffic management system (FAA 2014).

![Nominal Trajectory and Proposed Resolution](image)

**Figure 24: Proposed Conflict Resolution under DAG-TM concept. Used with permission of Mark Ballin (Green, Ballin, Wing, 2000)**

This project’s more fundamental/theoretical approach allows a more elegant and “study-able” solution than brute force collision avoidance methodologies. Adding these capabilities to current simulations would help optimize flight path efficiency in a more quantifiably examinable manner, thanks to the ability of this tool to numerically identify the uncertainty and interaction of aircraft based on the distance that separates them.
5.2 Future Work

The simulation tool is well-suited for additional studies in airspace characterization. The current simulation is capable of modeling class A and E airspace but it can easily be manipulated to model airport class airspace as well. One of the advantages of the particle representation within this simulation is that various other “particles” can be represented within the airspace besides aircraft. Airports can be modeled as particles within the simulation tool, and proximity to these objects changes the governing equations and behaviors of aircraft. Once aircraft enter the “awareness radius” of an airport, their navigation rules would mimic landing and/or holding patterns. Aircraft origin/takeoff and destination/landing locations, rather than being generated randomly, can be isolated to these airport object locations.

Pilot-in-the-loop simulations could easily be run with this simulation tool. The simulation framework assumes that the pilot of each aircraft is given information filtered by an on-board computer. This research focused on helping define a knowledge radius for each aircraft: how far out in the airspace does the pilot need to have awareness? Once an aircraft enters the knowledge radius, the pilot is commanded to maneuver the aircraft to avoid conflict. Within the simulation tool, delaying the maneuver once an aircraft has entered the knowledge radius would simulate pilot delay in response. Pilot delay is another nondeterministic property within the system that could easily be studied with this tool.

Additional areas of study within the simulation tool that could improve function and capability are examination of the SPH implementation within the tool. The current execution has multiple aircraft interaction requiring a separate maneuver for each nearby aircraft. However, the SPH methodology allows for the testing of single maneuvers that attempt to avoid two more or more conflicting aircraft simultaneously by manipulation of the kernel function.

The architecture of the simulation tool also allows for inclusion of more aircraft characterization data like emergency turn rate and/or engine-out data. The use of these kinds of data would allow further study of the effects of stochastic events within the
NAS. Particularly with engine-out data, it would be interesting to see how this type of chaotic event would affect velocities, altitudes, and ranges of various types of aircraft.

The nondeterministic properties varied within the simulation tool are determined at the initialization of those variables. Varying nondeterministic aspects of the system mid-simulation is an interesting angle of potential research as well. Including and varying large weather fronts, as mentioned earlier, would have impact on aircraft’s sensors and consequently the size of each aircraft’s awareness radius. Varying the size of the awareness radius non-deterministically as aircraft close in on weather fronts or other interference-inducing objects would be another very interesting feature of the NAS to explore and one which this simulation tool could be easily equipped to study.

There is a category of separation assurance functions that focus on conflict prevention (CP) which do not allow trajectory changes that knowingly create a new conflict. This, of course, is an effective way of maintaining separation assurance and reducing the number of conflicts. Since an intended use of this simulation tool is to enable further exploration of the current conflict resolution methodology as well as replace the methodology with other CD&R functions if desired, this capability can also be added to the tool in an effort to determine how uncertainty in the NAS affects a management scheme with CP in place.

A whole host of additional research could be explored by exercising and/or improving the defining characteristics of this simulation tool. The novelty of this research is in its focus on uncertainty quantification and its utilization of the SPH methodology to model aircraft interaction. This research provides a useful tool to the aerospace community for modeling potential decentralized models of the NAS.
References


Appendix

A-1 Aircraft Characterization Data

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Class E: 160/250 | 25000 |
| Airbus A320 (Delta Virtual Airlines, 2009) | Class A: 394/447
Class E: 360/394* | 39800 |
Class E: 325/371* | 41000 |
Class E: 390/425* | 43000 |
| Boeing 737 (Delta Virtual Airlines, 2013) | Class A: 410/486
Class E: 413/482* | 41000 |
| Boeing 747 (Delta Virtual Airlines, 2009) | Class A: 436/487
Class E: 390/436* | 45720 |
| Boeing 777 (Delta Virtual Airlines, 2014) | Class A: 374/462
Class E: 310/374* | 42000 |
| Boeing 787 (Boeing 787 Dreamliner, n.d.) | Class A: 195/593
Class E: 195/567* (limited data) | 43000 |
| Bombardier CRJ-200ER (Delta Virtual Airlines, 2014) | Class A: 394/466
Class E: 210/394* | 41000 |
| Cessna 172 (Cessna Aircraft Company, 1977) | Class A: N/A
Class E: 100/122 | 13500 |
| Embraer ERJ-170 (Shuttle America, 2008) | Class A: 240/320
Class E: 160/320* | 41000 |
| Goodyear Blimp (Goodyear Blimp, n.d.) | Class A: N/A
Class E: 20/50 mph | 10000 max
Class E: 3000 operational |
| Hang Glider (Hang Gliding, n.d.) | Class A: N/A
Class E: 30/50 mph | 18000 max
Class E: 1200 operational |
Class E: 170/280* | 35000 |
Class E: 84/135 mph (limited data) | 25000 |
| Powered Parachute (Inland Paraflite Inc., n.d.) | Class A: N/A
Class E: 23-27 mph (limited data) | 10000 |
| Robinson R22 (Robinson Helicopter Co., 2015) | Class A: N/A
Class E: 60/102 | 14000 |
Class E: 109/357* (limited data) | 60000 |
| Schweizer 1-26 Sailplane (Schweizer Aircraft Corp., n.d.) | Class A: N/A
Class E: 30/104 mph | 10000 |
| V-22 Osprey (NAVAIR, 2010) | Class A: 120/305
Class E: 180/280 | 25000 |
| VT e-SPAARO (C. Woolsey, personal communication, 2015) | Class A: N/A
Class E: 10/30 m/s | 2000 |

* large transports do not cruise in class E airspace, but will be found ascending/descending
Airbus A320 Data obtained from FlightAware.com (B. Roberts, personal communication, January 3, 2015)

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