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Exploration of Detect-and-Avoid and Well-Clear Requirements for Small UAS Maneuvering in an Urban Environment

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There is a growing demand in the United States for small Unmanned Aircraft Systems (UAS) to operate in urban environments. A key safety component of UAS traffic management is a Detect And Avoid (DAA) system to keep each UAS well clear of other traffic. RTCA, Inc., Special Committee 228 is currently working to define well clear and DAA system performance requirements for UAS transitioning to and from Class A airspace or special purpose areas. Those well clear and DAA system requirements are tailored to the performance characteristics of large UAS interacting with manned traffic in the NAS, and are not appropriate for small UAS operating in a cluttered urban environment at low altitudes. This paper presents the results of a preliminary concept exploration simulation study to characterize DAA system requirements for small UAS maneuvering in a cluttered urban environment. The study was conducting using prototype algorithms implemented for SAFIT™ (Safe Autonomy Flexible Innovation Testbed), a UAS platform under development that will enable safe flight testing of unproven autonomy applications by providing integrated flight protection including traffic and obstacle avoidance, flight envelope protection, and geospatial containment.

Nomenclature

ADS-B	= *Automatic Dependent Surveillance-Broadcast*
AGL	= *Above Ground Level*
A_o	= *Initial altitude of ownship aircraft*
A_1	= *Initial altitude of first traffic aircraft*
A_2	= *Initial altitude of second traffic aircraft*
A_3	= *Initial altitude of third traffic aircraft*
B_B	= *Buffer for ownship distance from building*
B_H	= *Building height*
CTOL	= *Conventional Take-Off and Landing*
D	= *Distance between buildings*
DAA	= *Detect and Avoid*
DAIDALUS	= *Detect and AvoID Alerting Logic for Unmanned Systems*
ft	= *Feet*
GC	= *Geometric Center*
GPS	= *Global Positioning System*
L	= *Length of corridor between buildings*
NAS	= *National Airspace System*
NMAC	= *Near-Mid-Air Collision*
s	= *Seconds*
SAFIT™	= *Safe Autonomy Flexible Innovation Testbed™*
TCAS	= *Traffic alert and Collision Avoidance System*
UAS	= *Unmanned Aircraft Systems*
UAV	= *Unmanned Aerial Vehicles*
UTM	= *UAS Traffic Management*

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V_o	= *Velocity of ownship aircraft*
VTOL	= *Vertical Take-Off and Landing*
V_1	= *Velocity of first traffic aircraft*
V_2	= *Velocity of second traffic aircraft*
V_3	= *Velocity of third traffic aircraft*
WCV	= *Well-Clear Volume*
Δ_1	= *First traffic aircraft distance from centerline*
Δ_2	= *Second traffic aircraft distance from centerline*
Δ_3	= *Third traffic aircraft distance from centerline*
τ_B	= *Building look-ahead time for building avoidance*

I. Introduction

There is a growing demand for access of Unmanned Aircraft Systems (UAS) to the United States National Airspace System (NAS). For manned aircraft, a key aspect of safety is the onboard pilot's ability to see and avoid traffic, using human judgement to remain "well clear" of other aircraft[1]. For unmanned aircraft, this see and avoid task is replaced by a Detect And Avoid (DAA) system. RTCA, Inc., Special Committee 228 has created Minimum Operational Performance Standards for integration of UAS in the NAS, including a quantitative definition of well clear and DAA system Minimum Operational Performance Standards. The initial work within the committee is focused primarily on large UAS transitioning to and from Class A airspace[2] or special purpose areas, with planned follow-on work to address more general integrated operation of large and small UAS within the NAS. The most challenging operating environment for small UAS is maneuvering at low altitudes in an urban environment.

While much work has been conducted on defining Near-Mid-Air Collision (NMAC) and Well-Clear standards[3] for large UAS transiting the NAS, the vehicle size, performance, and operating assumptions, and hence those NMAC and Well-Clear Volume (WCV) definitions are not applicable to small Unmanned Aerial Vehicles (UAV) maneuvering in an urban environment where they will not encounter a manned aircraft. For example, large UAV typically do not maneuver as nimbly as small UAV, and large UAV speeds, even at low altitudes, are assumed to be as high as 200 knots. In fact, the large UAS NMAC volume is considerably wider than a typical urban street. Thus, new Well-Clear definitions will need to be developed with appropriate assumptions for small UAV operating in an urban environment. A literature search reveals very few analyses to date on quantification of NMAC and WCV for small UAS urban maneuvering.

Adaptive Aerospace Group, Inc., (AAG), under a grant from NASA, is developing the Safe Autonomy Flexible Innovation Testbed (SAFIT™), which will enable safe flight testing of unproven autonomy applications, such as complex and/or nondeterministic systems. One key feature of the design is the SAFIT-Wrap™ wrapper, which will ensure safe flight evaluation of unproven prototype applications by providing integrated flight protection including traffic and obstacle avoidance, flight envelope protection, and geospatial containment[4]. One area of research that SAFIT™ is being designed to support is NASA's UAS Traffic Management (UTM) research, which is focused on small UAS maneuvering at low altitudes in an urban environment cluttered with buildings and other small UAS traffic aircraft.

This paper presents the results of a batch simulation experiment for SAFIT-Wrap™ as a conflict avoidance and flight envelope protection suite. Test scenarios were designed to simulate a small UAS maneuvering in an urban environment, including complex situations that the vehicle might be exposed to during UTM research work. The primary objective of the experiment was to evaluate the effectiveness of the SAFIT-Wrap™ prototype algorithms and parameter settings, such as buffer sizes and look-ahead times, for maintaining safe flight operations for the simulated vehicle in an urban environment. However, the experiment also addresses a larger goal of preliminary concept exploration towards developing WCV and NMAC definitions for small UAS maneuvering in an urban environment.

NASA's UTM concept of operations[5] is focused on "flexibility where possible and structure where necessary," which means that if multiple UAS are operating in an area, then a centralized traffic management system and operating in predefined lanes at set altitudes[6] will provide procedures for safe separation augmented by contingency procedures to manage off-nominal events. The NASA concept, which is still under development, includes incorporation of advanced onboard DAA systems as they become available. While centralized traffic management may be available in some urban areas, it is likely that future suburban or rural package delivery may require UAS to provide separation assurance from traffic and obstacles. Onboard separation assurance may also be needed within a controlled UTM environment to provide additional protection in the presence of non-normal and off-nominal events, such as failure of a vehicle to stay within its assigned lane or failure to meet assigned timing constraints. The results described in this paper are applicable to exploring DAA system performance requirements for an unmanned fixed-wing aircraft.

II. Simulation Platform

The simulation features the SAFIT-Wrap™ prototype software, which contains the traffic and obstacle avoidance, flight envelope protection, and geospatial containment logic as well as Ardupilot open-source autopilot software, a JSBSim open source aircraft simulation model, Flight Gear visualization software, and a data collection module. The SAFIT-Wrap™ algorithms receive traffic position and velocity information via simulated Automatic Dependent Surveillance Broadcast (ADS-B) and have access to information on obstacle polygons to be avoided as well as geospatial containment boundaries. Ardupilot uses the unofficial UAV standard formatting known as Mavlink, an in-flight interface language including features such as sender and receiver verification, checksum error detection, variable length custom messages, system status updates via periodic heartbeat, and position, velocity and attitude data. The SAFIT™ prototype UAS also uses this serial connection to send commands to the Ardupilot autopilot system. The performance of the SAFIT™ vehicle is simulated by using a similar small UAV predefined in JSBSim, but adjusting the aero-propulsive performance parameters to match the SAFIT™ vehicle. The vehicle design is a quad tilt-rotor vehicle with a high wing featuring an H-tail and redundant control surfaces. It features a Vertical Take-Off and Landing (VTOL) configuration with good cruise endurance supported by pivoting all four motor/propellers or a Conventional Take-Off and Landing (CTOL) configuration with more efficient cruise by optionally removing two of the motor/propellers, enabling a wide range of mission scenarios. Only CTOL flight is used in the simulation, since obstacle avoidance is more difficult at CTOL cruise speeds and without the option of hovering in place. The prototype design has a wingspan of 9 feet to meet anticipated payload requirements and is powered by four 15-inch fixed mid-pitch propellers with an estimated cruise speed of 40 miles per hour.

SAFIT-Wrap™ can communicate with ArduPilot via waypoints or direct control surface commands. For this experiment SAFIT-Wrap™ sends immediate waypoints to the Ardupilot flight control system, which in turn calculates control commands to navigate to the waypoints. This simulation was run in real time with the waypoints being generated at a rate directly proportional to the computational power of the hardware running SAFIT™. Onboard the UAV, ArduPilot executes on a Pixhawk PX4 flight controller and SAFIT-Wrap™ is hosted on a Raspberry Pi micro flight controller, as shown in Figure 1. Pre-simulation testing showed that a running rate of two Hertz was sufficient for Ardupilot's internal waypoint polling rate. In the simulation experiment, the desktop computer ran the SAFIT™ algorithms at a rate of roughly sixty Hertz, while the Raspberry Pi Micro runs SAFIT™ at approximately twelve Hertz. The SAFIT™ executive algorithm creates a sequence of "swept" waypoints to finely control the maneuvering behavior of the ownship, rather than issuing a single waypoint and leaving the maneuvering to Ardupilot.

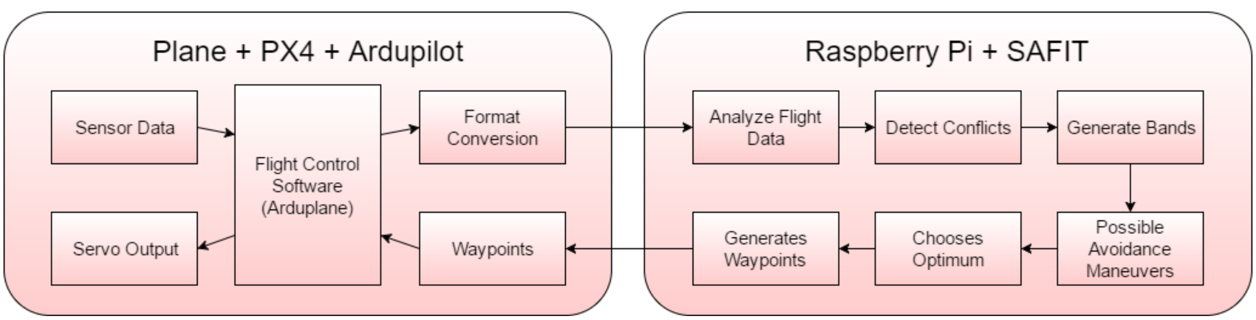

Figure 1. Block Diagram of SAFIT™ Hardware and Software.

III. Conflict Detection and Resolution

Maneuvering in an urban environment involves avoidance of stationary obstacles, such as buildings, as well as traffic aircraft. The obstacle and traffic aircraft conflict detection and resolution parameters used in the experiment are described in this section. Since SAFIT-Wrap™ is intended for use as a stopgap safety application, not as a strategic path planner, the look-ahead times used are relatively short and the conflict resolution algorithms employed find a single clear (conflict-free within the look-ahead times) heading and turn the vehicle towards it. Look-ahead time defines how the algorithm scans for conflicts by extrapolating the positions of the ownship and any traffic vehicles by the amount described by the look-ahead time and then using that position to detect nearby objects. Reactive and preventative bands are generated for any objects detected. When faced with a decision of turning left or right, the algorithms generally turns to the closest heading, but if the aircraft is already in a turn, continuing to turn in the same direction is preferred. Any brief gaps in receipt of information, such as traffic position updates or ownship Global Positioning System (GPS) data is internally extrapolated. In addition, any information received that does not pass an internal filter is discarded to guarantee optimum response to imperfect information.

A. Buffers for Obstacles, Traffic Aircraft, and Geospatial Containment

One of the highest priorities for a UAS in an urban environment is the guarantee of staying within a given geospatial containment volume. Preliminary vertical and horizontal buffers and look-ahead times for geospatial containment are shown in Figure 2. Only the vertical buffers and look-ahead times were used in the experiment; the horizontal buffers and look-ahead times for geospatial containment will be evaluated in a subsequent experiment. These buffers and look-ahead times were defined based on preliminary results from an initial simulation study to take advantage of the maneuverability of the vehicle while ensuring a low probability of violating the geospatial boundary. The geospatial containment vertical buffer of B_{GV} = 34 ft (10 m) is intended to keep the aircraft from impacting the terrain at 0 ft Above Ground Level (AGL) and remaining safely below the ceiling altitude of 400 ft AGL. A vertical look-ahead time of τ_{GV} = 1 s was used. The geospatial containment horizontal buffer of B_{GH} = 136 ft (40 m) is designed to keep the aircraft safely inside the geospatial containment area. The horizontal buffer is set to a larger value in SAFIT-Wrap™ in response to concerns from NASA Langley's UAS flight operations personnel about operating in test areas that are in close proximity to public roads and land.

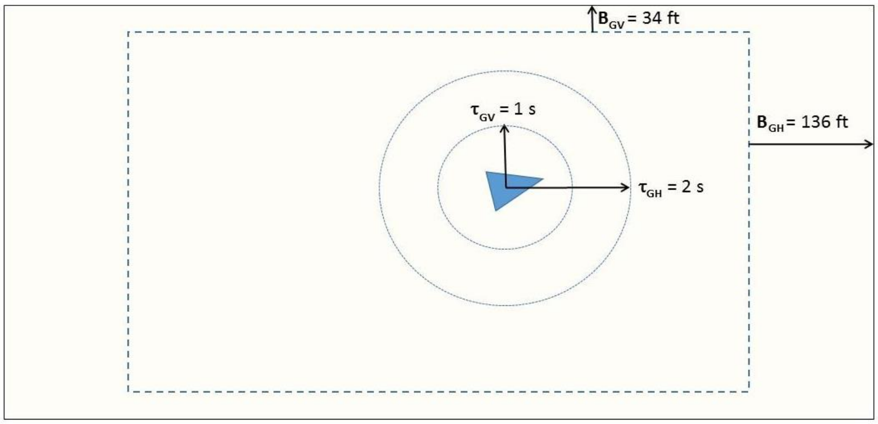

Figure 2. Vertical and Horizontal Buffers and Look-Ahead Times for Geospatial Containment.

Another consideration is that small UAS must stay clear of obstacles such as buildings, but what constitutes a safe distance has yet to be defined. For this experiment, a static buffer, B_B was defined around the edges of the building, as shown in Figure 3, which must be maintained between any building and the Geometric Center (GC) of the ownship aircraft. If the GC of the aircraft is closer to a building than B_B, this is considered a violation of the building buffer. Within this experiment, B_B values between 10 and 20 ft are evaluated. Note that the wingspan of the aircraft is approximately 10 ft, so if the GC of the aircraft is at the smallest buffer size of 10 ft, then the wing tip is only about 5 ft from the building. Detection and maneuvering to avoid traversing the building buffer begins at look-ahead time τ_B, as shown in Figure 3.

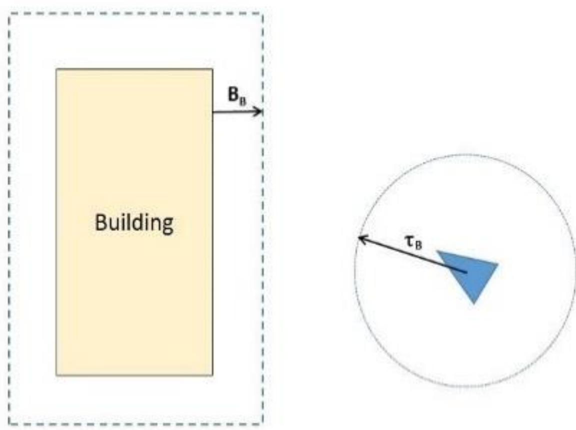

Figure 3. Buffer and Look-Ahead Time for Building Obstacle Conflict Detection and Resolution.

Finally, SAFIT-Wrap™ must also provide for avoidance of other aircraft. For manned aircraft operating in the NAS, the NMAC volume used by the Traffic alert and Collision Avoidance System (TCAS)[7] is a cylinder with a radius of 500 ft, which is approximately double the length of the full wingspan of the largest civil transport aircraft, and a half-height of 100 ft, which is double the height of the largest civil transport aircraft.

Clearly such a large NMAC volume would not be acceptable for small aircraft passing each other on an urban street. We assume that most small UAS operating in a cluttered urban environment would typically have a wingspan at or less than 10 ft and would have altitude sensing accuracy on the order of 10 ft at low operating altitudes. Thus, a preliminary NMAC volume for a small UAS maneuvering in an urban environment was defined as a cylinder with radius 10 ft and half-height 12 ft, as shown Figure 4. In order for two unmanned aircraft to use onboard automation to remain well clear of each other while passing on a narrow street, a smaller volume for DAA well clear is needed. A preliminary WCV, shown in Figure 4, was defined with radius 20 ft and half-height 24 ft, which is twice the radius and twice the height of the NMAC volume. A look-ahead time τ_T for detecting conflicts with traffic aircraft was held constant at 4 s throughout the experiment except for the last scenario, when a look-ahead time of 8 s was also evaluated. SAFIT-Wrap™ utilizes an algorithm developed by NASA Langley Research Center for detecting conflicts with traffic aircraft[8,9]. These short times were chosen due to the aircraft's ability to turn at 30 degrees per second.

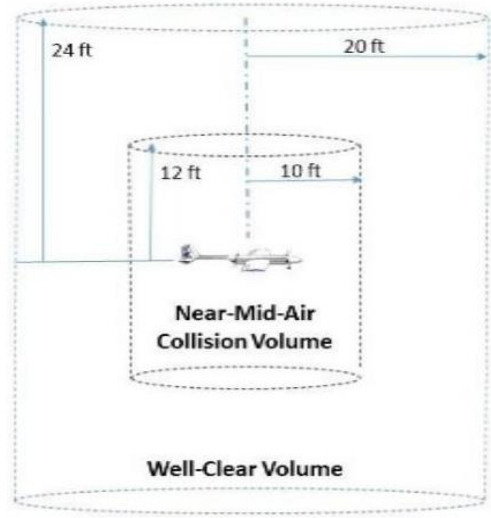

Figure 4. Near-Mid-Air Collision Volume and Well-Clear Volume.

B. Conflict Detection Band Generation and Resolution Maneuvering

To formulate a response to conflicts, avoidance "bands" are generated. Bands quantify a range of headings and vertical speeds that would result in the aircraft entering the detected conflicts in the near future. Simply stated, tracking/heading bands define an arc of headings that the ownship should avoid turning into and vertical speed bands depict a strip of possible vertical speeds that the ownship should avoid. Both vertical speed bands and heading bands are created for all conflicts, and the algorithm for identifying candidate resolution maneuvers considers lateral, vertical and combination lateral/vertical maneuvers to avoid the bands. In conflicts with traffic aircraft, the vertical speed bands can identify opportunities to pass safely above or below the traffic aircraft; however, when approaching geospatial containment boundaries and tall buildings, the vertical speed bands become completely saturated because no vertical speed change alone will resolve the conflict and lateral maneuvering is required.

Bands are generated for traffic aircraft, obstacle avoidance, and geospatial containment. The generation of bands for avoidance of traffic aircraft is accomplished using an algorithm from NASA's DAIDALUS (Detect and Avoid Alerting Logic for Unmanned Systems) software[8,9]. The generation of bands for avoiding obstacles, such as buildings, is described below. The generation of bands for geospatial containment is quite similar. The algorithms are designed to allow for additional bands to be created based on any other possible future avoidance targets, such as weather volumes or unauthorized airspaces, if the need should arise to define a conflict that does not fit any of the predefined criteria.

Conflict resolution algorithms designed for civil transport aircraft to avoid hazardous weather polygons or unauthorized regions of airspace typically navigate to a waypoint that is several miles from the obstacle to be avoided. For urban maneuvering, avoidance distances are considerably smaller, and in fact, skirting along the edge of an obstacle buffer or geospatial containment boundary may be desirable, making full use of the available urban airspace. Thus, the conflict resolution algorithm for SAFIT-Wrap™ is designed to calculate a trajectory that brings the vehicle tangential to the building buffer without crossing it. The algorithm allows the vehicle to asymptotically approach the building to a fixed distance of the building buffer for any shape of building from any arbitrary starting velocity, while also providing enough reaction time to turn away from the building if approaching it head on. For concave building shapes, the aircraft is able to fly into large concave areas where it is capable of maneuvering back out, while avoiding small concave areas that would trap the vehicle.

C. Complex, Multiple, and Prioritized Conflict Resolution

In an urban environment, UAS will frequently need to react to multiple conflicts at a time, and the algorithms must gracefully address cases where a satisfactory solution to multiple conflicts cannot be found. As described above, each avoidance protection is implemented with a buffer of additional protection space, which can be traversed when necessary to avoid a more important protection. The band generation algorithm supports multiple priority layers of bands. For this simulation experiment, two band layers were used, representing a high-priority and a low-priority conflict for each building, traffic aircraft, or geospatial containment boundary in conflict. Geospatial containment breaches, building collisions, and traffic aircraft NMAC violations were considered of equally high importance, and a set of high-priority bands to avoid these violations with zero buffer were defined. Crossing into a building buffer, traffic aircraft WCV, or geospatial containment buffer region was considered to be lower priority, and low-priority bands were generated for conflicts with these buffer regions. This method of defining band priority is completely extendable to any number of priorities, and could allow for additional lower-priority avoidance maneuvering, such as prioritizing aircraft avoidance over weather avoidance or prioritizing high population density building collision avoidance over zero population obstacle avoidance, such as trees. The downside of this approach is that each additional layer of priority adds computational complexity and additional computation time to the algorithm, and the need for detailed prioritization must be balanced against the speed of the algorithm.

The resolution algorithm uses the different levels of band priorities to choose the optimum course of action to minimize all-clear time with all current conflicts. Prioritizing the higher-level bands, the algorithm calculates the all-clear time based on the lateral and/or vertical maneuver needed to avoid each conflict, considering vehicle parameters such as maximum dive rate, maximum climb rate, current speed, minimum turn radius, maximum roll angle, and roll speed. An exhaustive algorithm is then used to find an optimal maneuver that minimizes the all-clear time for all conflicts, considering the optimum resolution of higher priority bands before considering the optimum resolution of lower priority bands. Again, the runtime of this algorithm is very susceptible to both the number of conflicts and the number of band priorities.

Three experiment scenarios, described below, were designed to simulate situations a UAS might encounter when operating in an urban environment. The scenarios were chosen for the maneuverability challenges they provide, supporting the tuning of buffer sizes and look-ahead times and affording an opportunity to make some observations about UAS urban maneuvering.

IV. Scenario One: Corridor Between Buildings with Oncoming Traffic

The first scenario, shown in Figure 5, was designed to assess the feasibility of multiple small UAS operating on a typical-width urban street without using lanes or assigning East/West altitude rules and without hovering capability. In the scenario, the ownship flies down a street between tall buildings on both sides while simultaneously avoiding a single oncoming traffic aircraft. The narrowest corridor between buildings is 50 ft wide, which is representative of a two-lane urban street with two 15-ft wide lanes for cars plus two 10-ft wide sidewalks. The widest corridor simulated is 90 ft wide, representing four 15-ft wide lanes for cars plus two 15-ft wide sidewalks. Building buffers for the narrowest corridor were set at 10 ft, 15 ft, and 20 ft, since larger buffers would have taken up too much of the street width.

At the beginning of each run, the ownship aircraft takes off from a nearby airport and flies towards the center of a corridor between two simulated buildings. The ownship is trying to reach a waypoint on the far side of the buildings, past the end of the corridor. Since the JSBSim simulation has built-in navigational and positional accuracy noise to represent inaccurate sensors, each set of parameter values is executed five times. The lateral position of the ownship typically varies a few feet left or right of the centerline at the entrance to the corridor, with an observed maximum deviation of less than 3.5 ft. The ownship also overshoots the target altitude and is as much as 15 ft too high and is in a shallow descent when it enters the corridor. This overshoot is due to the inertia of the aircraft as it approaches the altitude of the first waypoint. Occasionally the simulation

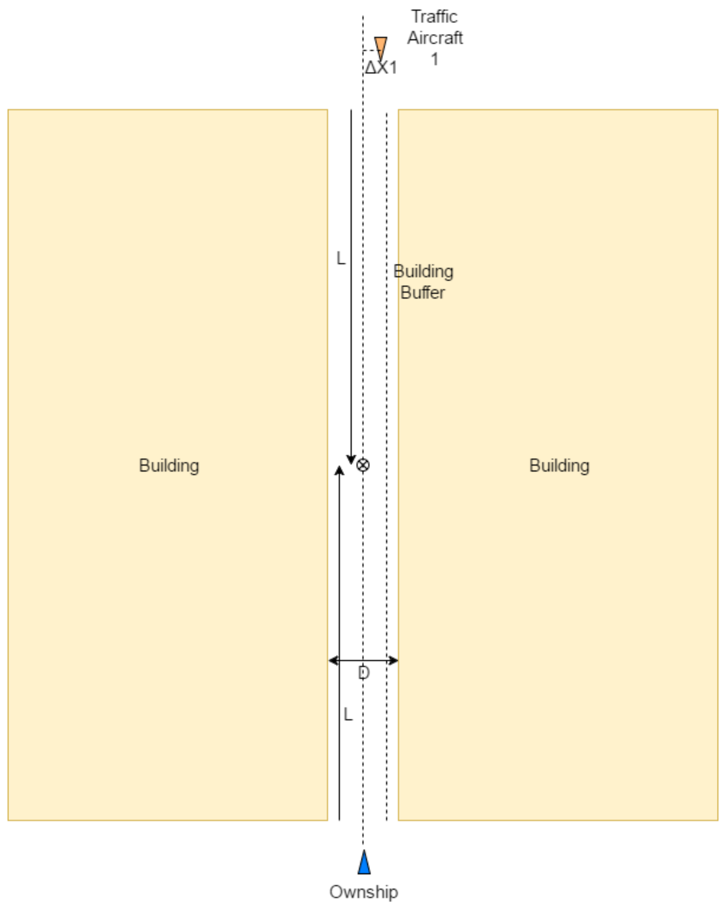

Figure 5. Building and Traffic Setup for Scenario One.

would fail to execute successfully on a run due to a program crash, and those runs were discarded, but there were always at least four replicates for each combination of variables.

The constants and variables used for Scenario one are shown in Table 1. The buildings are distance D apart. Once the aircraft reaches the edge of the corridor, an oncoming traffic aircraft is released at the far end of the corridor at the same current altitude as the ownship and distance L from the ownship. The traffic aircraft makes no maneuvers, traveling exclusively in a straight line along the corridor. The lateral position of the traffic aircraft varies between runs by distance Δ_X from the centerline of the corridor, moving it away from the path of the ownship. The traffic aircraft flies a straight path parallel to the buildings with no maneuvering during the scenario. The ownship can perform lateral and vertical maneuvers to avoid conflicts with the buildings and the traffic aircraft. If the SAFIT-Wrap™ software determines that there is not a sufficiently wide clear heading through the corridor, it can choose not to enter the corridor but instead try to go around the buildings. However, the ownship is already committed to entering the corridor when the oncoming traffic is spawned.

Table 1. Experimental Constants and Parameters for Scenario One.

D	Distance between buildings	50, 70, 90	ft
L	Length of corridor between buildings	650	ft
B_H	Building height (=ceiling for experiment)	400	ft
B_B	Buffer for building at D=50	10, 15, 20	ft
τ_B	Look-ahead time for building avoidance	2, 5, 8	s
V_O	Velocity of ownship aircraft	17	m/s
A_O	Initial altitude of ownship aircraft	200	ft AGL
V_X	Velocity of traffic aircraft	12, 17, 22	m/s
A_X	Initial altitude of traffic aircraft	Same altitude as ownship	ft AGL
Δ_X	Traffic aircraft distance from centerline	[0, D/2-B_B], incremented by 5	ft

In the analysis of simulation results, WCV violations are classified into three levels of severity. Green violations occur when the vehicle traverses the WCV by less than 15% of its total width. These violations occur mostly due to the SAFIT-Wrap™ software pathing tangentially to the WCV which, due to sensor noise/jitter and flight disturbances occasionally causes the aircraft to slip inside the WCV. These violations are not considered failures in this analysis, but their existence indicates that the algorithm needs to be adjusted to maintain an additional buffer around the WCV instead of creating a tangential path to its edge. Yellow violations occur when the vehicle traverses the buffer by more than 15% but less than 50%. These violations are typical of situations where the aircraft does not have sufficient look-ahead time to make an early enough decision to maneuver. While not considered failures, they are undesired and in an ideal scenario the aircraft would not be in such close proximity to the NMAC volume. Red violations occur when the vehicle traverses the buffer by more than 50%. These occur mostly when the look-ahead time is too small and the aircraft does not have time to adjust its path. Based on the selected size of the WCV, red violations have a high likelihood of collision and are considered failures.

The results from Scenario One are described in the following subsections in three different categories, based on the distance between buildings, which was the most significant parameter influencing the results.

A. Scenario One Results for 90-ft Corridor Width

This section describes the results for Scenario One where the distance between buildings was 90 ft. Traffic velocities were varied through 12m/s, 17m/s, and 22 m/s to simulate UAS traffic aircraft that were slower than the SAFIT™ vehicle, roughly the same speed, and faster than SAFIT™, respectively. The final parameter that is varied in this scenario is the initial lateral position of the traffic aircraft. The traffic aircraft starting location is varied systematically from the center of the corridor to within 5 ft of one of the side buildings.

Of these 1340 trials, the aircraft never penetrates the building buffer, and all variants of the parameters allowed for successful runs with no yellow or red WCV violations. There were 214 green WCV violations; however, most of these were quite small. These only occurred in cases where the traffic aircraft started in the range of an offset of 0 to 15 feet from the center of the corridor. This makes logical sense, as the amount of maneuvering required for the ownship aircraft to avoid the oncoming aircraft is inversely proportional to the oncoming aircraft's distance from the centerline. These violations were spread relatively evenly across all other parameter settings, though a slightly higher concentration occurred when the building buffer was 15 ft and 20 ft, presumably because there was less room for maneuvering to avoid the WCV. The WCV penetration distance averaged 0.12 ft, 0.22 ft, and 0.23 ft for a building buffer size of 10 ft, 15 ft, and 20 ft, respectively. The maximum penetration that was seen was 3.26 ft, which occurred when the building buffer was 15 ft, building look-ahead time was 2 s, and traffic velocity was 17 m/s. However, further analysis of the WCV penetrations larger than 2 ft showed that there is no significant correlation between the size of the building buffer and the WCV penetration distance in this category for Scenario One.

Figure 6 is the vertical profile heat map for the runs in this category, and Figure 7 is the bird's-eye heat map. These present an overlay of all of the runs for this category with heat maps of the ownship vehicle routes, with density represented by color ranging from red for the most common routes to light blue dots for as few as one run and with a dark blue background showing the areas where the vehicle did not travel. The large red blocks in the bird's-eye view represent the buildings. The buildings are not shown in the vertical profile because they would obscure the data. To capture vehicle maneuvers before and after the corridor, these heat maps begin 330 ft before the corridor and extend beyond it, with the near edge of the buildings at 0 ft and the far edge of the buildings at 650 ft. As discussed earlier, the vertical profile shows that the ownship enters the corridor as much as 15 ft above the target altitude and is in a shallow descent when it enters the corridor.

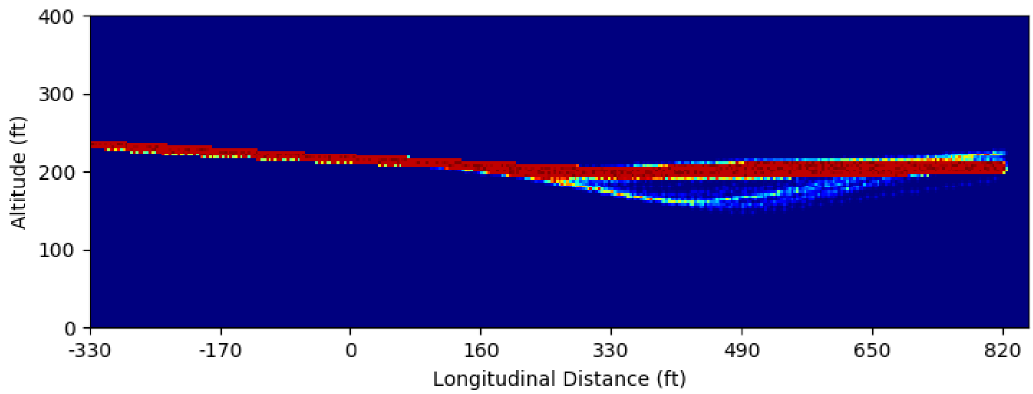

Figure 6. Vertical Profile Heat Map for 90 ft Corridor in Scenario One.

As shown in Figure 6, the ownship invariably chooses to decrease its altitude, rather than climb, when it detects that there is a conflict with the traffic aircraft. Figure 7 shows that the aircraft makes a lateral shift of about 5-10 ft halfway down the corridor, which is near the point of the conflict with the oncoming traffic aircraft. The conflict resolution algorithm creates a path in which the conflicts are resolved in the least amount of time both beneath and to the side, based on the geometry of the cylinder. Analysis of the 214 green WCV violations reveals that these violations are consistently located near the bottom rim of the WCV cylinder, i.e., the ownship turns and descends to avoid the conflict, but clips the lateral edge of the cylinder before reaching a safe altitude to pass beneath the WCV. This raises a question about the use of a cylindrical WCV. The absolute closest point of approach distances from the ownship to the traffic aircraft during the green WCV violations were always larger than the horizontal WCV radius; thus, of minimum impact to safety. It might be worth considering an alternative geometry to provide more flexibility for highly maneuverable small UAS. A spherical or ellipsoid WCV would make more intuitive sense for algorithmic processing, data analysis, and for future multi-rotor/hovercraft. However, this could restrict customization of the dimensional avoidance parameters, which may be necessary since GPS altitude is substantially less accurate than GPS latitude/longitude accuracy. None of the other parameters had a significant effect on performance in this category.

B. Scenario One Results for 70-ft Corridor Width

The second category is the 70-ft corridor, with 1336 runs and the same varied parameters as the category above. Of these trials, there were 20 building buffer violations and 7 building collisions. Additionally, there were 126 green traffic WCV violations, 45 yellow traffic WCV violations, and 5 red traffic WCV violations with 22 NMAC violations.

All 20 of the building buffer penetrations occurred when the buffer was at its maximum setting of 20 ft, leaving only a 30-ft wide corridor for the ownship to maneuver within to avoid the traffic aircraft. When the ownship turned away from the oncoming traffic, it became in conflict with the building, and the resolution algorithms had to prioritize between traversing the traffic aircraft's WCV or the building buffer. Because of the short time to react, in several cases, over-corrective maneuvering resulted in the ownship crashing either into the building or the traffic aircraft. Four of the seven building collisions along with six of the twenty WCV transgressions occurred when the traffic aircraft was laterally offset by 5 ft, the building buffer was 20 ft, and the building look-ahead time was 2 s. Another traffic collision and four more of the building buffer traversals occurred when the building look-ahead time was increased to 5 s. Yet, when the building look-ahead time was increased to 8 s there were no building buffer traversals. Clearly, building look-ahead time is a critical parameter.

It can be seen in the vertical profile heat map (Fig. 8) that a portion of the runs climb during the approach to the buildings. Each of these runs had the maximum building buffer setting of 20 ft and the ownship was initially positioned slightly to one side of the corridor, necessitating maneuvering to enter the corridor, which caused the resolution algorithm to determine that the vehicle could not enter the corridor and generated a resolution maneuver that attempted to climb the aircraft over the buildings. The initiation of the climb maneuver then decreased the speed of the aircraft enough that the resolution algorithm chose a path into the corridor. This resulted in the aircraft performing a slow climb until it reached the corridor. The lateral maneuvering before entering the corridor can be seen in the bird's eye heat map (Fig. 9). Similar to the first category, all of the WCV violations occurred when the traffic aircraft was within 15 ft of the scenario centerline, bringing it into conflict with the ownship's path. Fifteen of the twenty-two NMAC violations occurred when the traffic aircraft was directly centered in the corridor, and all of them occurred when the building buffer was its largest value of 20 ft. Examination of these cases revealed that the ownship would attempt to turn away from the traffic aircraft, only to detect the conflict with the buffer for the building and prioritize not crashing into the building over traversing the WCV of the traffic aircraft. The NMAC violations are correlated to the velocity of the traffic vehicle, such that when the traffic is traveling at 12 m/s, 13% of runs ended in an NMAC violation; at 17 m/s, 35% of runs ended in an NMAC violation; and at 22 m/s, 46% of runs ended in an NMAC violation. This is intuitive since the faster traffic aircraft affords the ownship less time and space to perform avoidance maneuvers. The average horizontal WCV penetration was around 4 ft for all of these cases, while the vertical WCV penetration increased from 4 ft to 9 ft as the traffic aircraft increased in speed. This indicates that the resolution algorithms originally attempted

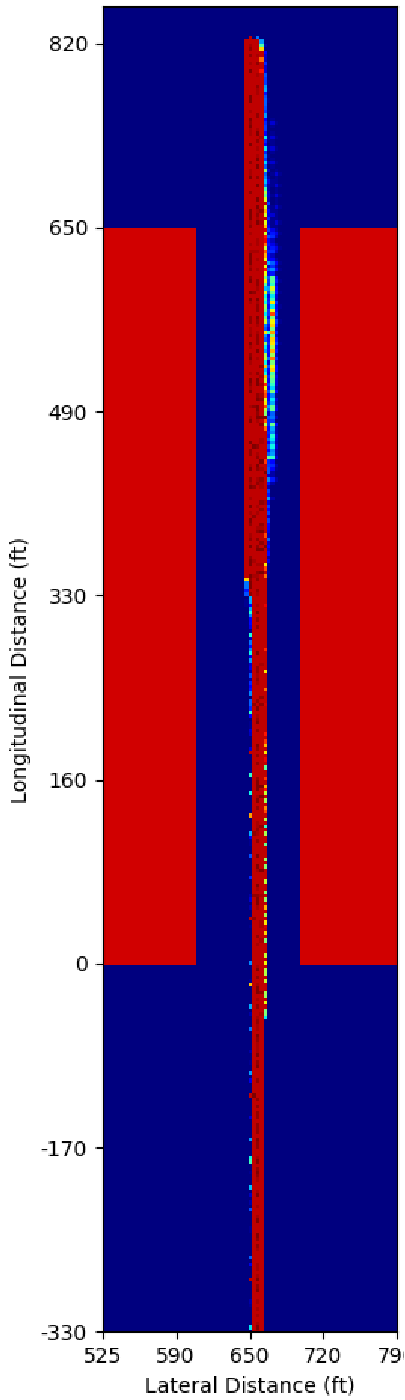

Figure 7. Bird's-Eye Heat Map for 90 ft Corridor in Scenario One.

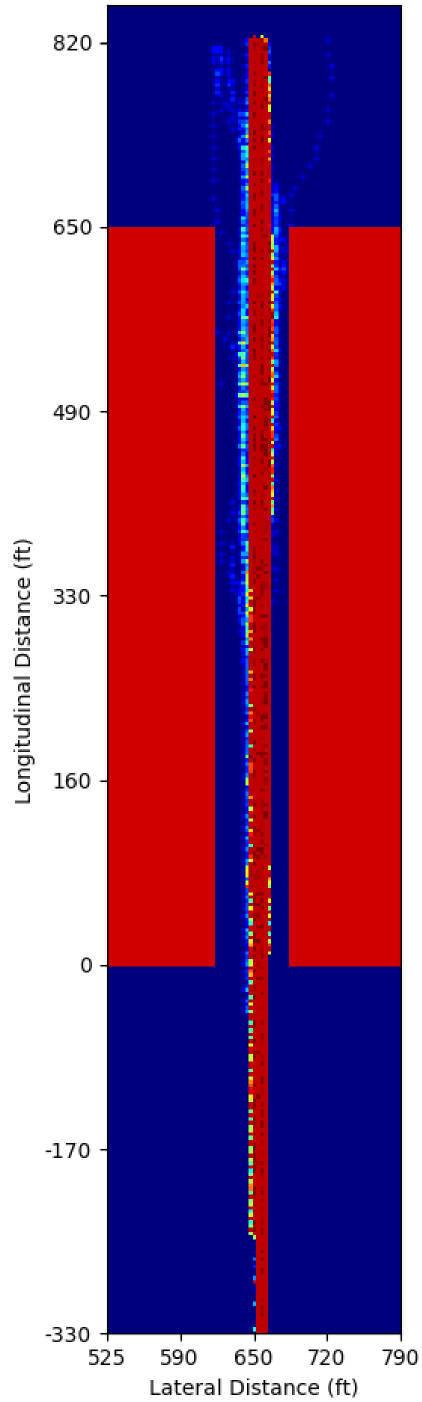

Figure 9. Bird's-Eye Heat Map for 70 ft Corridor in Scenario One.

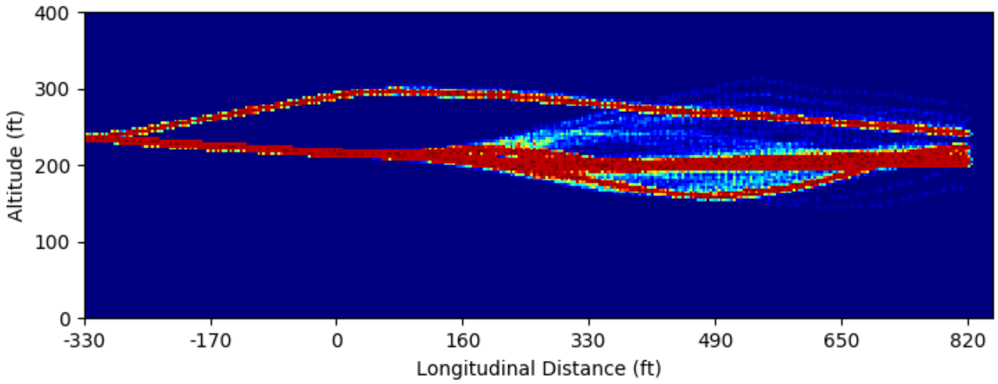

Figure 8. Vertical Profile Heat Map for 70 ft Corridor in Scenario One.

to make a track change, detected the building buffer, and changed from turning to descending to avoid the traffic aircraft, but did not have enough time to fully avoid the WCV violation. From Figures 8 and 9 as discussed above, it can be seen that the ownship made exclusively vertical speed changes in order to avoid the oncoming aircraft because of the narrowness of the maneuvering area, with shallow vertical maneuvers being sufficient to avoid slower oncoming traffic and steeper maneuvers required for faster oncoming traffic.

C. Scenario One Results for 50-ft Corridor Width

The third category is the 50 ft corridor, with 1340 runs. Figures 10 and 11 show the vertical profile heat map and bird's eye heat map for these runs, respectively. Across these runs there were 388 building buffer penetrations and 320 of those were building collisions. In this category, the building buffer size had a sizeable impact on the success of each run.

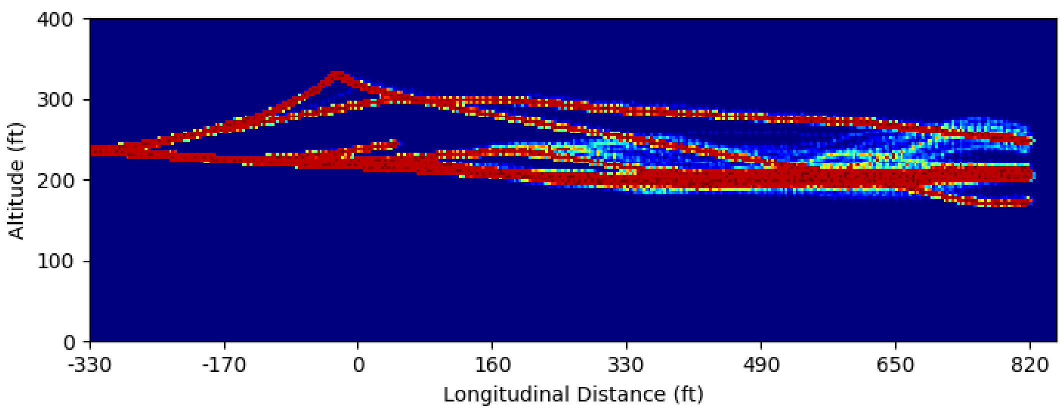

Figure 10. Vertical Profile Heat Map for 50 ft Corridor in Scenario One.

Runs where the buffer was at its minimum size of 10 ft had the lowest number of building buffer penetrations at 21, but 19 of those resulted in building collisions. For the 15-ft building buffer, there were 66 buffer penetrations but only 2 ended in building collisions, and with the 20 ft buffer, there were 301 building buffer penetrations, resulting in 299 building collisions. Drilling down, we see that when the buffer was 10 ft, all of the building buffer penetrations and building collisions occurred when the building look-ahead time was 8 s. All but one of the building buffer penetrations occurred when the velocity of the traffic aircraft was 17 or 22 m/s. This would indicate that the smaller building buffer with the higher building look-ahead time is more likely to incur a resolution reaction that pushes the aircraft into a WCV violation with the oncoming traffic aircraft. With 33 WCV violations at a building look-ahead time of 8 s and only 10 WCV violations when the building look-ahead time was shorter than 8 s, it is clear that the ownship ends up being forced into the building buffer more frequently with the longer look-ahead time.

The 15-ft buffer runs with a building look-ahead time of 8 s resulted in no building buffer violations and no collisions. With a look-ahead time of 5 s, there were 46 building buffer violations with no collisions, and with a 2 s look-ahead time there were 20 building buffer violations with 2 collisions. Both collisions and 29 of the 66 buffer penetrations occurred when the traffic airspeed was 22 m/s.

The runs with the building buffer parameter set at 20 ft had interesting results because the possible corridor for flight was only 10 ft wide, leaving no room for maneuvering to avoid the oncoming aircraft or even to allow for navigation inaccuracies. When the building look-ahead time was set at 8 s, the resolution algorithms invariably chose to try to avoid the corridor entirely and to fly around the buildings, as seen in Figure 11. However, when the building look-ahead time was 2 or 5 s, the resolution algorithm still tried to avoid the corridor, and since there was not enough time to maneuver, exclusively failed by collision with a building. As expected, this shows that there is no way for the aircraft to safely approach and enter the 10-ft wide maneuvering corridor, and without a high enough look-ahead time, the situation cannot be detected in time to make a maneuver to safety.

In the 50-ft corridor category, there were 81 WCV violations, none of which resulted in NMAC violations. Of these WCV violations, there were 60 green violations and 21 yellow violations. The runs with the 10 ft building buffer contained all of the yellow violations and 22 of the green violations. The yellow violations were nearly evenly spread between runs with the traffic velocity at 17 and 22 m/s, while none occurred with the traffic velocity at 12 m/s, which appears to indicate that there was a closure rate threshold leading to worse traffic violations. With a building buffer of 10 ft, the WCV violations occurred mostly when the building look-ahead time was 8 s, indicating that the more conservative building look-ahead time forced the aircraft closer to the traffic. The runs with the building buffer set to 15 ft contained the remaining 38 WCV violations, all of which were green. Most of these WCV violations occurred when the building look-ahead time was 5 s, once again indicating that when the conflict with the traffic aircraft caused the ownship to turn slightly towards the building, this caused a building conflict that triggered a larger resolution reaction in the case of the 5-s look-ahead time vs. the 2-s look-ahead time, causing the ownship to turn back towards the traffic and resulting in a narrower corridor to dodge the traffic aircraft's WCV. No WCV violations occurred with the buffer at 20 ft, because the ownship never entered the corridor with the buffer set to 20 ft.

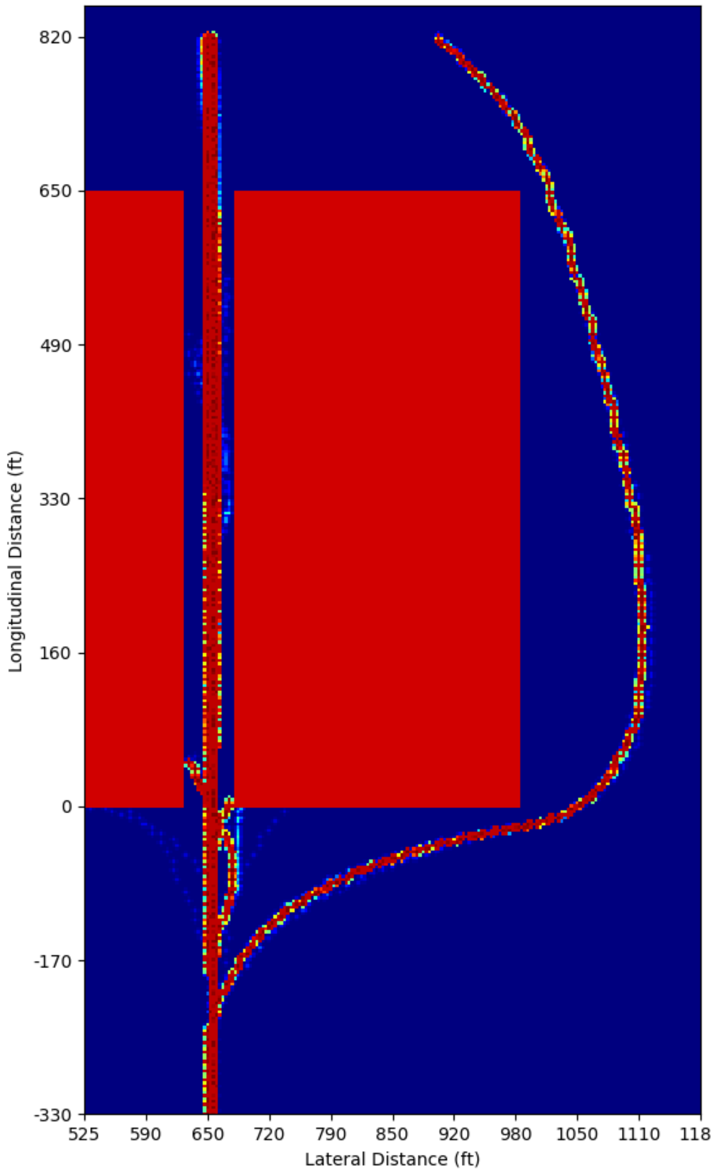

Figure 11. Bird's-Eye Heat Map for 50 ft Corridor in Scenario One.

D. Down-Select of Parameter Settings for Later Scenarios

After completion of the runs for Scenario One, preliminary analysis of the data was used to down-select some of the parameter settings for Scenarios Two and Three to focus on multiple traffic aircraft within parameter settings of interest. By eliminating ineffective parameter settings, more parameters of interest with respect to the traffic aircraft could be explored without encountering an exponential explosion of runs. For the distance between buildings, D, it was determined that a corridor width of 50 ft would be too narrow for lateral maneuvering to avoid crossing traffic, and a corridor width of 90 ft would not be challenging enough, so a distance D = 70 ft was chosen for the later scenarios. In Scenario One cases with a 70-ft distance between buildings, building look-ahead times of 2 s and 5 s were problematic, resulting in some building buffer violations and in WCV violations and even traffic collisions, while a building look-ahead time of 8 s appeared to provide more stability in maneuvering to avoid both traffic and buildings. Examination of the effects of building buffer size on the 70-ft corridor width results showed that the minimum building buffer size of 10 ft, which allowed more maneuvering room for avoiding traffic, appeared to be adequate building protection in Scenario One in that there were no building collisions or building buffer violations. Thus, the combination of 70-ft distance between buildings with the 10-ft building buffer and the 8 s look-ahead time, which yielded 100% successful runs in Scenario One, was adopted for the later scenarios.

V. Scenario Two: Corridor Between Buildings with One Oncoming and One Crossing Aircraft

The second scenario, shown in Figure 12, adds a crossing street and a traffic aircraft flying along the crossing street (perpendicular to the ownship aircraft) that must be avoided. The constants and parameters for Scenario Two are shown in Table 2. The buildings on both the main and crossing streets are a constant distance D = 70 ft apart, the building buffer B_B is constant at 10 ft, and the building look-ahead time τ_B is constant at 8 s.

The traffic aircraft are initially positioned to stage the multiple traffic aircraft conflicts at or near the center of the intersection at time T, when the ownship, if it has not maneuvered, would have travelled distance L, which is 330 ft since entering the corridor. Time T is approximately 5.9 s. When the traffic aircraft are released, they travel at a constant speed parallel to their respective corridors without making any maneuvers. They make no attempts to avoid each other or the ownship vehicle and do not react if they collide, merely passing through each other and continuing.

Traffic aircraft one, which is the oncoming aircraft, is released when the ownship enters the corridor and travels at constant speed (12, 17, and 22 m/s) in a straight line, parallel to the buildings. The initial position Δ_{X1} relative to the centerline ranges from 20 ft left of centerline to 20 ft right of centerline, in increments of 10 ft. Traffic aircraft one is initiated in a position such that at time T, at its given velocity, it will arrive at a point that ranges from 20 ft before the intersection to 20 ft after the intersection, in increments of 10 ft.

Traffic aircraft two, which is the crossing aircraft, is released when the ownship enters the corridor and travels at constant speed (12, 17, and 22 m/s) in a straight line on the centerline of the crossing street. Traffic aircraft two is initiated in a position such that at time T, at its given velocity, it will arrive at a point that ranges from 20 ft before the intersection to 20 ft after the intersection, in increments of 10 ft.

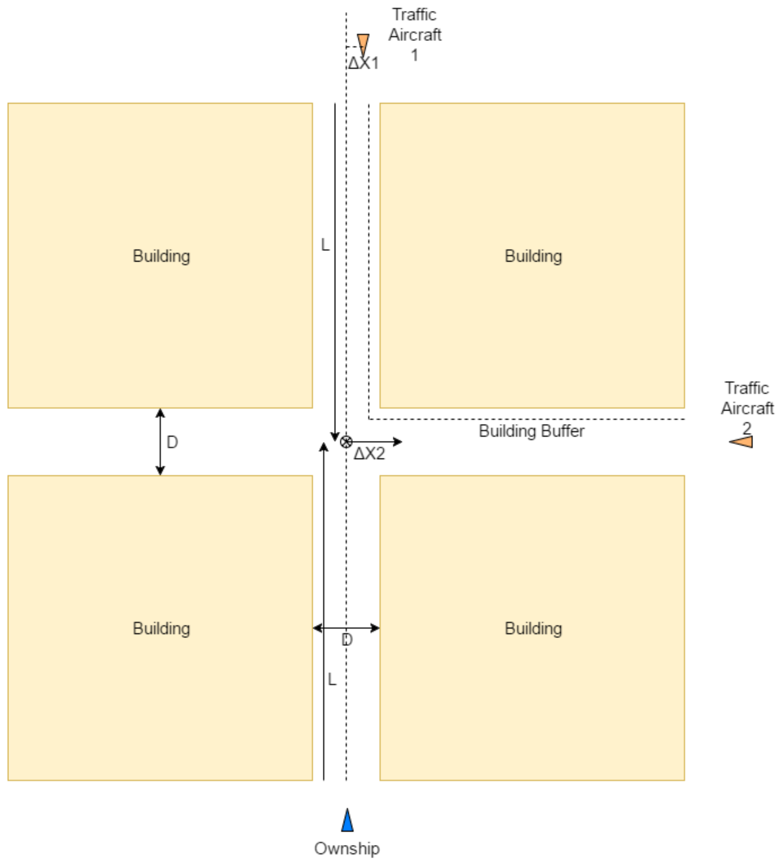

Figure 12. Building and Traffic Setup for Scenario Two.

A. Results for Scenario Two

Scenario Two consisted of 1120 total runs, during which the parameters varied were: oncoming traffic velocity, crossing traffic velocity, oncoming traffic aircraft centerline distance, oncoming traffic aircraft crossing distance, and crossing traffic aircraft crossing distance. Despite the fact the ownship was maneuvering to avoid two traffic aircraft corridor and the low building buffer with a high look-ahead time.in close proximity, there were no building buffer penetrations or collisions, which is most likely due to the wider corridor and the low building buffer with a high look-ahead time.

Table 2. Experimental Constants and Parameters for Scenario Two.

D	Distance between buildings on both streets	70	ft
B_B	Buffer for building	10	ft
B_H	Building height (=ceiling for experiment)	400	ft
τ_B	Look-ahead time for building avoidance	8	s
L	Length down corridor to center of crossing street	330	ft
V_O	Velocity of ownship aircraft	17	m/s
A_O	Initial altitude of ownship aircraft	200	ft AGL
V_{X1}	Velocity of oncoming aircraft	12, 17, 22	m/s
A_{X1}	Initial altitude of oncoming aircraft	200	ft AGL
Δ_{X1}	Oncoming aircraft distance from centerline	-20, -10, 0, 10, 20	ft
V_X	Velocity of crossing aircraft	12, 17, 22	m/s
A_X	Initial altitude of crossing aircraft	200	ft AGL
Δ_{X2}	Traffic aircraft lateral position when ownship has travelled distance L	-20, -10, 0, 10, 20	ft

There were, however, 912 WCV violations, although none resulted in an NMAC violation. Of the WCV violations, 902 were green violations, and only 10 were yellow violations. The distance of closest approach between the ownship and either traffic aircraft was over 20 ft in all cases, indicating a maximum WCV penetration of 4 ft. As shown in Figures 13 and 14, a combination of descending and lateral maneuvers are used to avoid the traffic aircraft. All WCV violations occur between the oncoming traffic aircraft and the ownship aircraft, and in every case the ownship aircraft clips the lower front edge of the oncoming traffic aircraft WCV while descending to pass below it. The yellow violations do not have a clear correlation to any other parameters, thus indicating that they are not affected by the position or velocity of the crossing traffic, but are simply a result of slow reaction time from the ownship, compounded by positional sensor errors, similar to the green violations. As noted previously, the ownship aircraft enters the corridor higher than its intended altitude by approximately 15 ft in most runs. Since the traffic aircraft begins flying at the same height as the ownship aircraft is when it enters the corridor and the ownship aircraft is descending slightly, as the scenario progresses the traffic aircraft will be slightly above the ownship when the conflict is detected, which is a factor in why the algorithm regularly chooses to fly beneath the traffic aircraft.

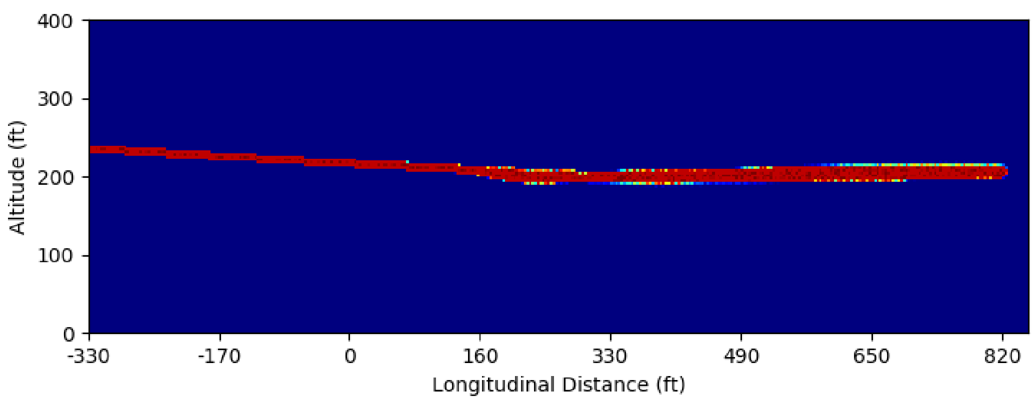

Figure 13. Vertical Profile Heat Map for Scenario Two.

Detailed analysis of the runs resulting in the yellow WCV violations as well as the deepest green WCV penetrations reveals that when the ownship first detects the conflicts, the vertical resolution maneuvers initiated are not sufficiently steep to avoid the WCV violations, probably due to position uncertainty. Once the need for a steeper descent is recognized, there is insufficient time to execute a steeper maneuver to avoid the WCV violation. As stated previously, this problem could be alleviated by adding a small additional buffer around the WCV to allow for sensor error and potentially also helped by increasing the traffic look-ahead time. Since more than 80% of runs had a green WCV violation with the algorithm taking the same path in every run, it is apparent that an increase in traffic look-ahead time and a small buffer around the WCV are necessary for this set of parameters in this type of scenario.

D. Refinement of Parameter Settings for Scenario Three

Most of the parameter ranges for Scenario Three were kept the same as Scenario Two for consistency in comparing results. An extra aircraft was added in Scenario Three and altitude differences were introduced, with the goal of creating even more difficult conflict situations than were seen in Scenario Two. Since the Scenario Two results seemed to indicate the need for an increase in traffic look-ahead time, which would likely be even more imperative in complex conflicts, two traffic look-ahead times were used in Scenario Three: 4 s and 8 s.

V. Scenario Three: Corridor Between Buildings with One Oncoming and Two Crossing Aircraft

The third scenario, shown in Figure 15, is similar to the second scenario with the inclusion of an additional crossing aircraft traveling in the opposite direction from traffic aircraft two. Constants and parameters for Scenario Three are shown in Table 3.

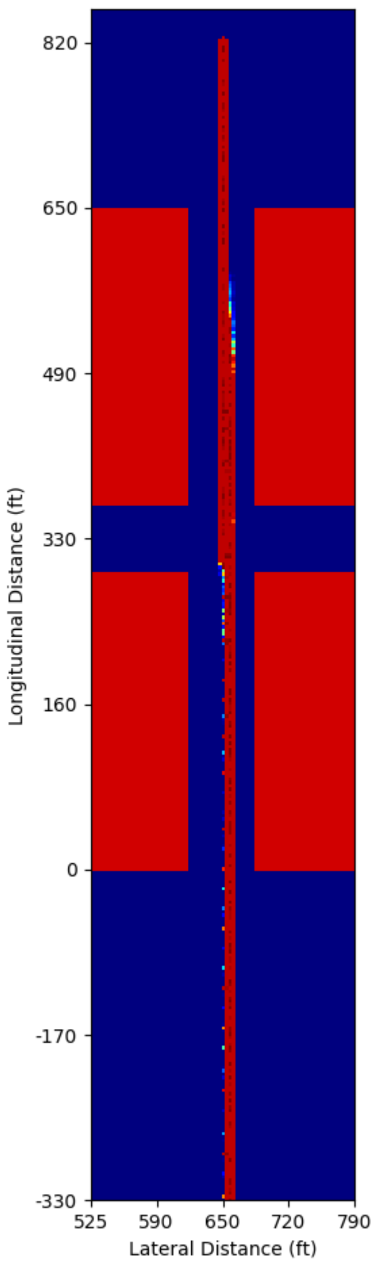

Figure 14. Bird's-Eye Heat Map for Scenario Two.

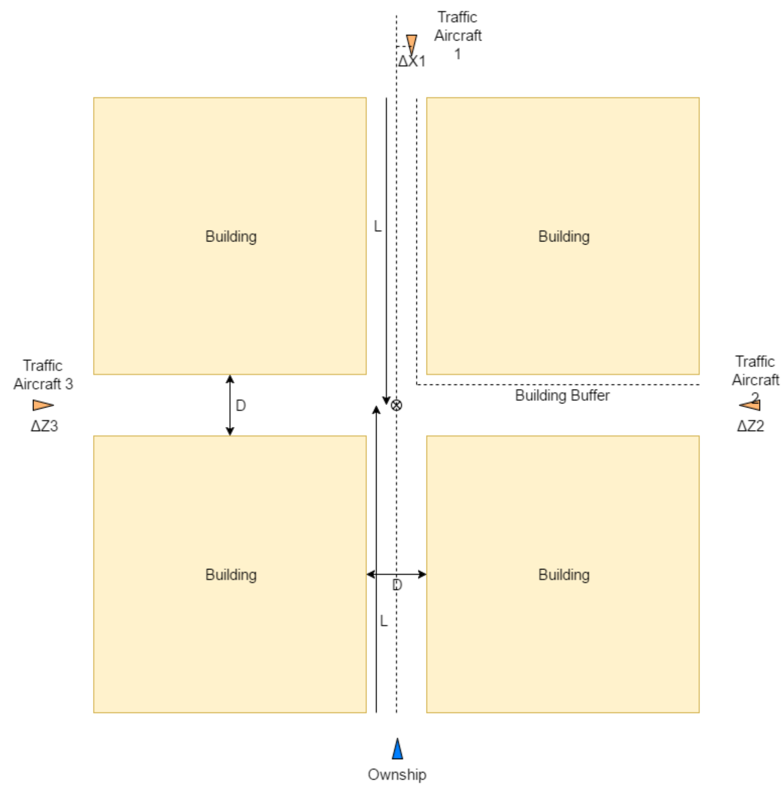

Figure 15. Building and Traffic Setup for Scenario Three.

The distance D between the buildings, building buffers B_B, and building look-ahead time τ_B are all held at the same constant values as in Scenario Two. Initial position and velocity parameters for the traffic aircraft are set such that when the parameters are zeroed, all traffic aircraft would meet in the middle of the intersection. The traffic aircraft iterate through a series of velocities and starting positions such that they arrive at their designated locations with respect to the center point at the same time.

However, the range of parameters tested are quite different from Scenario Two. While all traffic aircraft iterated through the constant speeds of 12, 17, and 22 m/s and the respective positions to maintain the same meeting conditions as above, each aircraft only iterated through its own position offset. Traffic aircraft one iterated through the same range of Δ_X as in Scenario Two. Traffic aircraft two; however, iterated through values of 0, 20, and 40 ft above the ownship's altitude. Traffic aircraft three iterated through values of 0, 20, and 40 ft below the ownship's altitude. The

Table 3. Experimental Constants and Parameters for Scenario Three.

D	Distance between buildings on both streets	70	ft
B_B	Buffer for building	10	ft
B_H	Building height (=ceiling for experiment)	400	ft
τ_B	Look-ahead time for building avoidance	8	s
L	Length down corridor to center of crossing street	100	m
V_O	Velocity of ownship aircraft	17	m/s
A_O	Initial altitude of ownship aircraft	200	ft AGL
V_{X1}	Velocity of oncoming aircraft	12, 17, 22	m/s
A_{X1}	Initial altitude of oncoming aircraft	200	ft AGL
Δ_X	Oncoming aircraft distance from centerline	-20, -10, 0, 10, 20	ft
V_{X2}	Velocity of crossing aircraft	12, 17, 22	m/s
A_{X2}	Initial altitude of crossing aircraft	200, 220, 240	ft AGL
V_{X3}	Velocity of crossing aircraft	12, 17, 22	m/s
A_{X3}	Initial altitude of crossing aircraft	200, 180, 160	ft AGL

traffic aircraft did not make vertical speed changes, that is, they continued at whatever their assigned starting altitude was without climbing or descending.

The objectives behind introducing the altitude differences in the conflicts were twofold: 1) to examine the ability of the algorithms to define and select vertical resolution maneuvers when only narrow bands of altitude were available for maneuvering, and 2) to counteract the resolution algorithm's historic choice to perform vertical speed changes over track changes by introducing situations where vertical maneuvering would be less desirable. Under the "worst case scenario" parameter set, traffic aircraft one, two, and three would be at relative altitudes of 0, 40, and -40 ft, respectively. This aimed to provide a very difficult scenario to resolve.

Analysis of results for Scenario 3 is split into two categories: results for a 4 s traffic look-ahead time, and results for an 8 s traffic look-ahead time.

A. Results for Scenario Three with Four-Second Traffic Look-Ahead Time

This category contained 1212 runs, which included 71 building buffer penetrations leading to 68 building collisions and 914 WCV violations leading to 214 NMAC violations. As shown in Figures 16 and 17, the ownship detects only the conflict with oncoming traffic aircraft one, which has a higher closure rate, as early as 160 ft into the corridor and chooses either a steeper descent, a climb, or a slight lateral-only maneuver to manage that conflict, depending on the altitude and lateral position of the oncoming aircraft. Well after initiating that maneuver, the ownship then detects the additional conflicts with crossing traffic aircraft two and three, because their closure rates are slower. In many cases, the maneuver initiated to avoid traffic aircraft one is incompatible with avoiding traffic aircraft two and three, and the ownship has very little time to initiate a new maneuver, even if a potential maneuver can be identified to avoid all of the simultaneous conflicts. Fifty-six of the building buffer penetrations and fifty-four of the collisions occurred

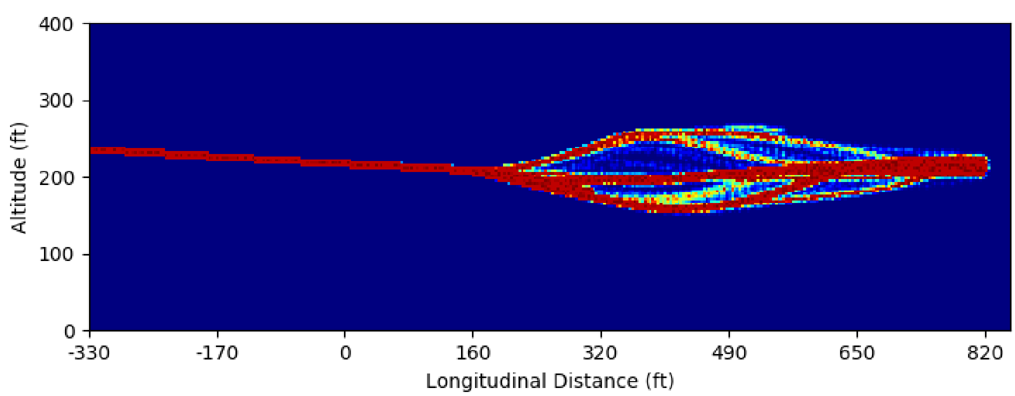

Figure 16. Vertical Profile Heat Map for Scenario Three with 4-s Look-Ahead.

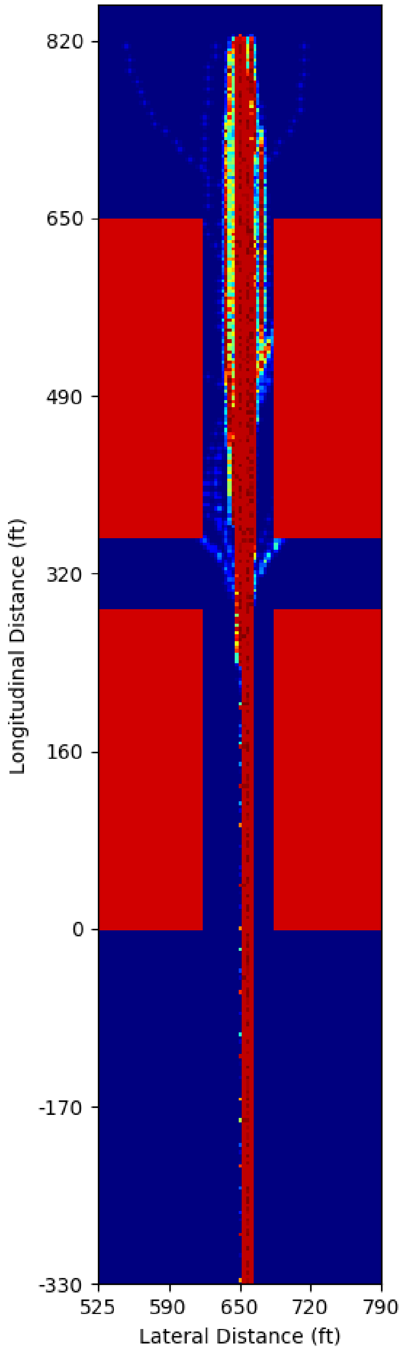

Figure 17. Bird's-Eye Heat Map for Scenario Three with 4-s Look-Ahead.

when the oncoming traffic aircraft centerline distance was between 0 and 20 feet, crossing traffic aircraft one vertical position was at 0 feet, and crossing traffic aircraft two vertical position was at -40 feet, a particularly difficult combination of parameter settings.

Interestingly, as may be seen in Figure 17, all of the lateral divergences leading to building buffer violations and building collisions are initiated near the center of the crossing street. Thus, these are not maneuvers made prior to the intersection to avoid traffic conflicts, but rather these are maneuvers made to expedite the time to clear an NMAC or WCV violation once the violation has already occurred. This reveals a deficiency in the conflict resolution prioritization logic, which finds the optimum maneuver that minimizes the all-clear time for all conflicts, considering the optimum resolution of higher-priority bands before considering the optimum resolution of lower-priority bands. In many cases the solution that minimizes all-clear time for the three traffic conflicts penetrates a lower-priority building buffer so deeply that either the wing of the ownship impacts the side of the building or in some cases the vehicle makes a sharp turn towards the building.

B. Results for Scenario Three with Eight-Second Traffic Look-Ahead Time

This category included 1202 runs with zero building buffer penetrations and 81 WCV violations with no NMAC violations. The vertical profile and bird's eye heat maps for these runs are shown in Figures 18 and 19, respectively. It is apparent that the increased traffic look-ahead time allowed for better detection and pre-emptive avoidance maneuvers. Of the 81 WCV violations, 36 were green violations, 44 were yellow violations, and 1 was a red violation with a WCV penetration of 13.5 ft. All 81 WCV violations occurred when the velocity of crossing traffic aircraft two was 12 m/s. The slower velocity for aircraft two served to spread out the footprint of the traffic to be avoided, creating a more difficult conflict problem to resolve. Since the traffic avoidance algorithm is based on volume avoidance, the algorithm will have the best results when creating avoidance maneuvers in response to a lower amount of total traffic volume versus a higher one. Related to this, it can also be concluded that the algorithm would have the hardest time calculating an ideal resolution maneuver when the volumes covered by the traffic aircraft intersect the least: that is, when the magnitude of the union of the volumes covered by the traffic vehicles is the largest. Of the 44 yellow and 1 red WCV violations, the majority occurred when the union of the volumes was at its maximum.

The longer look-ahead time resulted in noticeably less aggressive maneuvers for conflict avoidance and resolution. Comparing Figure 19 to Figure 17, it can be seen that the 8-s traffic look-ahead time results in more effective use of the lateral maneuvering room within the corridor than the 4-s traffic look-ahead time, both before the intersection to avoid conflicts and after the intersection while recovering from WCV violations. Figure 18, when compared against Figure 16, shows that the 8-s traffic look-ahead time allows for much less steep vertical maneuvers for conflict avoidance because they are initiated sooner. Figure 18 also shows that in a few cases the ownship vehicle climbs more quickly after passing the traffic aircraft, likely due to being in a WCV violation setting and selecting a maneuver that minimizes the all-clear time for all conflicts.

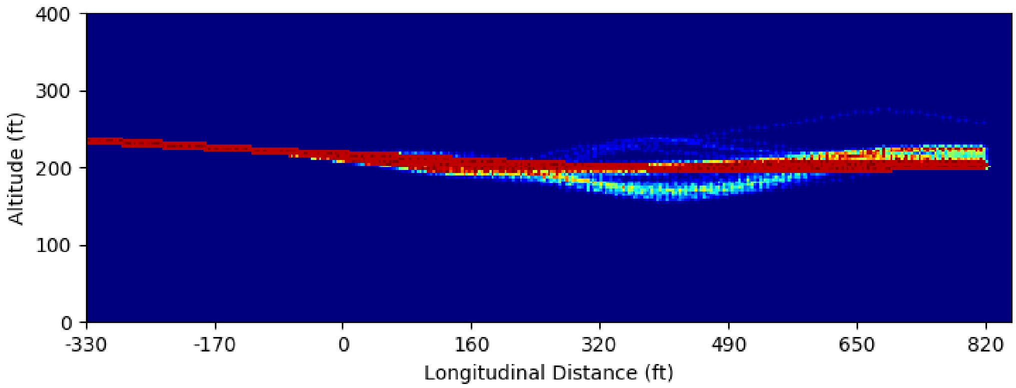

Figure 18. Vertical Profile Heat Map for Scenario Three with 8-s Look-Ahead.

V. Conclusions

The performance of the prototype SAFIT-Wrap™ traffic and obstacle conflict detection and resolution algorithms was assessed in a batch simulation study using challenging scripted scenarios representative of a small UAS maneuvering in an urban environment. The scenarios were designed to evaluate the effectiveness of the SAFIT-Wrap™ prototype algorithms and parameter settings, such as buffer sizes and look-ahead times, for maintaining safe urban flight operations. Additionally, a number of general observations can be made from the study results about small UAS maneuvering in an urban environment, including assessment of the preliminary WCV and NMAC definitions that were developed for the study. All of the numerical results and conclusions are dependent on the vehicle maneuvering performance assumptions and conflict detection and resolution algorithms used in the study.

From the simulation results, it appears that an additional buffer of 5 ft should be added around the WCV to allow for ownship and traffic aircraft position uncertainty and navigation errors. In the simulation study, the resolution maneuvers were designed to path tangentially to the WCV with no buffer, and sensor noise/jitter and flight disturbances occasionally caused the ownship aircraft to slip inside the traffic aircraft's WCV as much as 4 ft. Analyses of these cases shows that the addition of this small buffer to the WCV avoidance calculations should eliminate these minor WCV violations. In all cases, the initial resolution maneuver attempted, which was insufficient to avoid the WCV violation, was not limited by any vehicle performance parameters, such as maximum dive rate, minimum turn radius, or roll speed. Thus, it appears that with the additional buffer a successful resolution maneuver would have been performed to successfully avoid the green WCV violation in most if not all cases. Before operational implementation, the size of this additional traffic WCV buffer must, of course, be validated by analysis and testing in an actual urban operational environment.

The first scenario was focused on maneuvering to avoid a single oncoming traffic aircraft in a corridor between buildings, such as an urban street. The results from this scenario showed that, as expected, larger building buffers reduce the chance of building collisions but interfere greatly with maneuverability due to the reduced maneuvering corridor size, defined as the distance between buildings minus the two building buffers. This, in conjunction with high building look-ahead times, can even make it impossible for the aircraft to enter the corridor. However, if a building buffer is too small, the SAFIT-Wrap™ algorithm may maneuver into a building in an attempt to avoid traffic. Based on the assumptions and algorithms in this study, successful avoidance maneuvering was demonstrated for a distance between buildings of 70 ft using a building buffer of 15 ft or less, representative of a two-lane street with 15 ft-wide lanes and buildings set 20 ft back from the street. With a 70-ft distance between buildings, a building buffer of 10 ft was shown to be adequate to protect against building collisions for vehicles with a 10-ft wingspan.

In Scenario Two, which added a second traffic aircraft on a cross street timed to arrive at the intersection in close proximity to the arrival of an oncoming traffic aircraft, the SAFIT-Wrap™ algorithms invariably chose to perform a vertical avoidance maneuver. Despite the challenging nature of this scenario, all runs resulted in a closest point of approach to traffic aircraft of 20 ft or more, so with the addition of a 5 ft buffer around each traffic WCV mentioned above, it appears that all of these runs should have been successful in avoiding all conflicts.

Scenario Three added a second crossing aircraft and introduced altitude variation to the crossing traffic aircraft to create even more challenging scenarios. Scenario Three showed that longer traffic look-ahead times are critical to successfully navigating crowded traffic situations. A 4 s traffic look-ahead time resulted in 75% of runs containing a WCV violation and 18% of runs ending in an NMAC violation. However, extending that look-ahead time to 8 seconds reduced the WCV violations to 6% of runs, of which none ended in an NMAC violation. The longer look-ahead time

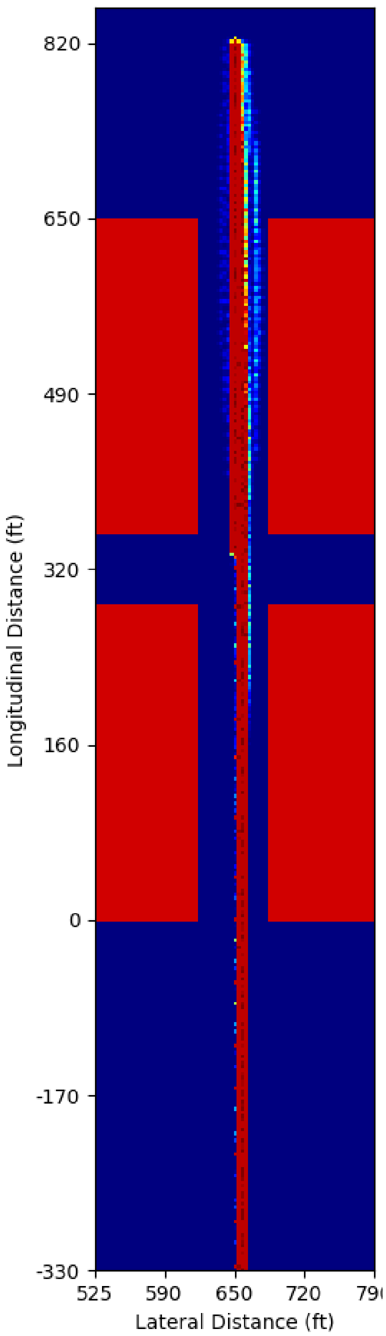

Figure 19. Birds-Eye Heat Map for Scenario Three with 8-s Look-Ahead.

also reduced building buffer penetrations from 72 to zero. Scenario Three results also showed that if the avoidance maneuver is initiated sooner, a less severe avoidance maneuver is required, particularly when responding to multiple conflicts that are detected sequentially. The less last-minute and sporadic the maneuvers are, the lower the chance that the vehicle makes an abrupt turn towards a building or another traffic aircraft faster than it can react to that new conflict. The results from Scenario 3 show that a combination of greater traffic and building look-ahead times allow the algorithms to make appropriate decisions with regards to buildings in addition to traffic avoidance. These results also indicate that a smaller building buffer size with larger look-ahead times for both buildings and traffic would provide a solid balance between safety and maneuverability.

Because of the simplicity of the SAFIT-Wrap™ resolution maneuvers, while an increase in the buffers and look-ahead time parameters will decrease the likeliness of violations, increasing them too much will prevent the vehicle from completing mission objectives. This is observed in Scenario One, where flying down the 50-ft wide corridor with the most conservative building buffer value is deemed impossible by the algorithm and instead the vehicle attempts to fly around the entire obstacle. Since the resolution maneuvers are simple maneuvers rather than multiple-waypoint paths, if very long building look-ahead times are used, then a clear straight path will not be found on a curving street or moving towards a T intersection where there are buildings on both sides of the street. However, if more moderate building look-ahead times are used, then the algorithms will find a suitable clear straight path to move along a curved street or towards a T intersection, although this can also result in travelling towards a dead end with no turn-around room if intelligent longer-term path planning is not employed.

In an ideal setting, the parameters for the SAFIT-Wrap™ algorithms would allow the vehicle to safely navigate any obstacles while still allowing for the completion of the mission. However, this may not always be possible, particularly in the presence of unpredictable maneuvering by traffic aircraft. It is reasonable to conclude that purely reactive safety algorithms with imperfect information are unlikely to be able to reasonably avoid collisions in dense and complex urban environments. From this it follows that some form of preventive safety must be additionally implemented. The simple SAFIT-Wrap™ algorithms with appropriate parameter settings seem to be capable of handling simple encounter cases that would be expected in the presence of a "rules of the road" style pathing requirement, particularly in lower traffic density such as in rural and suburban environments. These "rules of the road" would use lanes and altitude conventions to limit the majority of complex, unexpected, and unplanned traffic and building interactions, removing most of the fringe cases that are difficult to handle. For urban environments of the future, which may involve large numbers of UAS operating in close proximity, SAFIT-Wrap™ could work effectively in conjunction with some form of UTM system, which would control the number of aircraft operating along or crossing a given street or region of airspace, reducing the likelihood of encountering complex traffic situations. While the use of UTM systems to fully control UAS traffic in urban environments has been proposed, autonomous onboard conflict avoidance software, such as SAFIT-Wrap™, is likely a vital component of future management of UAS traffic in rural and suburban environments not under UTM control and for safe operations in the presence of off-nominal and non-normal operations in UTM-controlled environments.

While the SAFIT™ vehicle itself is VTOL and hover capable, it was not treated as such during this simulation experiment, in order to focus on the much harder problem of a fixed-wing UAV. A UAV capable of hovering in place, ascending and descending without a heading change, and capable of having zero ground speed would make conflict resolution trivial in comparison. The bands resolution approach employed in SAFIT-Wrap™ could easily be extended in the future to take advantage of these capabilities for a VTOL UAV.

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References

[1] US Department of Transportation Federal Aviation Administration, General Operating and Flight Rules, 19 CFR Part 91.113, 2013.

[2] RTCA, Inc., "Terms of Reference, RTCA Special Committee 228, Minimum Performance Standards for Unmanned Aircraft Systems," RTCA Paper No. 109-13, May 20, 2013.

[3] Jack, D. P., Hoffler, K. D., and Johnson, S.C., "Exploration of the Trade Space Between UAS Maneuver Performance and SAA System Performance Requirements," NASA CR-2014-218264, May 2014.

[4] Johnson, Sally, and Couch, Jesse, "A Wrapper Paradigm for Trusted Implementation of Autonomy Applications," *17th Aviation Technology, Integration, and Operations (ATIO) Conference*, June 2017.

[5] Kopardekar, Parimal, Rios, Joseph, Prevot, Thomas, Johnson, Marcus, Jung, Jaewoo, and Robinson, John E., III, "Unmanned Aircraft System Traffic Management (UTM) Concept of Operations," *16th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference*, June 2016.

[6] Warwick, Graham, "Street Sense," *Aviation Week and Space Technology*, February 6-19, 2017.

[7] US Department of Transportation, Federal Aviation Administration, Introduction to TCAS II, version 7, November 2000.

[8] Munoz, Cesar, Narkawicz, Anthony, Hagen, George, Upchurch, Jason, Dutle, Aaron, Consiglio, Maria, and Chamberlain, James, "DAIDALUS: Detect and Avoid Alerting Logic for Unmanned Systems," *IEEE/AIAA 34th Digital Avionics Systems Conference*, Prague, Czech Republic, September 2015.

[9] Hagen, G., Butler, R., and Maddalon, J., "Stratway: A Modular Approach to Strategic Conflict Resolution," *11th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference*, September 2011.