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Computing Proximity to Threat Along Uncertain Trajectory to Support Urban Air Mobility

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Summary

Many airspace threats affect the selection of a flight route, such as terrain, physical obstacles, adverse weather, and special-use airspace, among others. Threat avoidance during Urban Air Mobility (UAM) and Low Altitude Mobility (LAM) flights is especially challenging due to their lower cruising altitudes. These operations may be exposed to buildings, towers, trees, terrain undulations, etc., along much of their flight route. Moreover, these low-altitude flights in urban environments are expected to encounter very busy airspace, increasing the workload associated with threat avoidance. The Proximity to Threat (PtT) function aims to support onboard or remote pilots by computing the risk from geospatial threats in the airspace along an aircraft's flight path. The threats are both static entities and dynamic airspace restrictions that have been modeled and stored in geo-referenced mapping databases. The flight path may be specified by waypoints, airways, or similar discrete route elements or by a time series of closely spaced position and altitude points. Flight path uncertainty can also be taken into account by assuming both the position and altitude to be sampled from two normal distributions, each being specified by a mean and variance. PtT uses this additional information to verify that the flight path remains clear of threats along a wider path or if a position is reached earlier or later than anticipated, assuring the pilot or operator that there will be an available safety margin even if the aircraft deviates due to one or more occurrences of unexpected wind gusts, mechanical failures, airspeed changes, collision avoidance maneuvers, etc. The client can specify an uncertainty confidence level to bound the set of trajectories evaluated for threats so that the confidence level corresponds to the client's risk tolerance under the expected conditions. PtT can be used as a pre-flight planning tool to determine a safe route through known threats and in-flight to avoid emerging or changing threats. In this report, we present the PtT function, discuss how the trajectory uncertainty is incorporated into the PtT function, and describe the use of this PtT function in a representative scenario.

Nomenclature

Acronyms

ATM-X	Air Traffic Management eXploration
CERTAIN	City Environment for Range Testing of Autonomous Integrated Navigation
eVTOL	electric vertical take-off and landing
FAR	Federal Aviation Regulations
GA	general aviation
HITL	human-in-the-loop
LAM	Low Altitude Mobility
SM	safety margin
PDF	probability density function
PtT	Proximity to Threat
SDSP	Supplemental Data Service Provider
sUAS	small Unmanned Aircraft Systems
SWS	System Wide Safety
TFR	Temporary Flight Restriction
UAM	Urban Air Mobility

Variables

c	fraction of peak height of Gaussian density
μ	mean
σ	standard deviation
Z	Z score

1 Introduction

New air traffic management approaches are being explored to maintain airspace safety, even with the expected significant increase in urban area operations. Emerging urban area operations include Urban Air Mobility (UAM), e.g., air taxi operations, and Low Altitude Mobility (LAM), e.g., small Unmanned Aircraft Systems (sUAS) (or drones) delivery operations (Ref. 1–3). In the remainder of this document, we refer to both these emerging concepts as UAM. UAM flights are expected to operate under new regulations that redistribute flight responsibilities to an on-board or remote pilot, automation, and ground personnel separate from traditional air traffic control (ATC) (Ref. 4).

A major responsibility for ensuring safety is detecting and avoiding threats along the flight path. Because flights will operate at low altitudes through an urban environment, they may encounter numerous threats, including tall buildings, airspace restrictions (e.g., stadium Temporary Flight Restrictions (TFRs)), and areas with reduced navigation signals. Moreover, the location and timing of threats may not be known before takeoff and may also change during flight. The location/timing of *some* threats will be known with certainty during pre-flight planning and can be avoided through prudent route selection. Knowledge of the location/timing of *other* threats may be imprecise before flight due to the uncertainty of forecasts in urban environments, uncertainty of demand for flights (e.g., air taxis), etc. Prudent route selection, in this case, requires a trade-off between maximizing performance (i.e., fastest flight time or lowest energy usage) and an acceptable level of risk. A less direct route may be required to ensure that a high-consequence threat will be avoided. Finally, some threats may arise *during* flight, such as:

- A weather system may arrive earlier than forecast, prompting a path deviation or destination change;
- Winds may shift and necessitate a landing approach from a different direction;
- Winds may be stronger than predicted and require diversion to a closer destination;
- Mechanical issues or higher than anticipated congestion may require diversion to an alternate destination;
- The route may be blocked and a detour required due to a newly-issued TFR, a medical flight that popped up, or a rogue aircraft that is flying erratically;
- A construction crane may change location or extent, either requiring avoidance or opening a more direct route that was previously not available; and
- A new forecast or airspace constraint is published, among others.

For these emergent threats, the flight route may need to be modified once airborne. Incoming information from disparate sources must be continually evaluated, and risks to the route must be detected. The sustained high workload during low-altitude operations in busy airspace could result in a threat being overlooked. An unnoticed threat could lead to reduced safety margins, rule violations, or incidents/accidents. Many safeguards are in place for traditional commercial flights that ensure a high level of safety. To also achieve a high level of safety and make the nascent UAM industry viable, pilots and operators may also benefit from safeguards, particularly through automation and support services. We propose the Proximity to Threat (PtT) function as such a safeguard.

The PtT function supports the route evaluation process. PtT continuously monitors the expected route to account for a multitude of threats and preemptively alerts the pilot or operator of any threats closer than a client-specified distance. Moreover, because the location or timing of some monitored threats may be uncertain, the pilot/operator can specify a desired detection confidence level, thereby specifying the potential route that should be considered. PtT would not alert for threats affecting lower likelihood predicted routes. It also may not be aware of all possible threats. Correspondingly, PtT supplements but does not eliminate the need for other in-flight threat detection and response technologies.

The rest of this document is organized as follows. In Section 2, we describe the PtT algorithm. In Section 3, we show how it was utilized onboard a drone, and as part of a supplemental service provider, and in Section 4, we summarize our findings and suggest future work.

2 Proximity to Threat

The Proximity to Threat (PtT) function informs the pilot/operator of geospatial threats along the flight path. In Subsection 2.1, we define threats and describe how they are represented; in Subsection 2.2, we describe how the flight path is specified; and, finally, in Subsection 2.3, we describe the algorithm to compute the PtT metric.

2.1 Threats

We generally use the term *threat* to represent any hazard to flight. A threat could result in a decrease in safety margin (e.g., flying closer than desired to an area with predicted turbulence), a flight rule violation (e.g., inadvertent entry into restricted airspace), or an accident (e.g., collision with a building). Threats can be physical entities, such as buildings, antennas, trees, or hills, or abstract entities, such as a Temporary Flight Restrictions (TFRs), areas with reduced GPS satellite reception, or areas of adverse weather.

Threats are represented as extruded polygons that encapsulate the threat's hazardous vertical and horizontal features. Thus, a tree is approximated by a 2-D polygon that fully encases the maximum horizontal extent of the trunk, branches, and foliage; the bottom of the polygon is the ground, and the top of the extruded polygon is the elevation of the maximum vertical extent of the tree. As another example, a special use airspace that resembles an upside-down wedding cake can be modeled as multiple polygons, each with a horizontal extent and a bottom and top elevation to bound the vertical extent. Threats are stored in a geo-referenced mapping database and can be updated as new threats emerge or existing threats expire.

2.2 Flight Path

The flight path can be specified either as a flight plan (a list of 3-D way-point coordinates and speeds at way-points), a specific 4-D trajectory (a time series of position and altitude), or as a probability density function (PDF) of possible 4-D trajectories. If specified as a flight plan, a 4-D trajectory is predicted using information about the aircraft (e.g., size, weight, make/model, number of rotors/engines, drag coefficient), expected weather conditions (e.g., wind direction, wind speed, wind variability, temperature), and flight environment (e.g., navigation precision, surveillance precision) (Ref. 5). If the necessary factors are known precisely, a single trajectory can be accurately predicted. However, that is typically not the case, and weather forecasts, aircraft performance, surveillance data, and flight control system (or pilot) action, among others, each contribute to uncertainty in the aircraft's position and altitude. Thus, the trajectory is represented as a PDF. A Gaussian distribution is assumed; hence, the path is defined as a time series of position mean and variance, and altitude mean and variance, e.g., a series of vectors of the form [`time`, `latitude-mean`, `longitude-mean`, `altitude-mean`, `latitude-variance`, `longitude-variance`, `altitude-variance`]*. The trajectory is updated and PtT is recomputed as new information (e.g., actual position, weather updates, etc.) is received.

2.3 Algorithm

The algorithm determining whether the flight is within a client-specified distance from any known threats is straightforward, except for handling trajectory uncertainty.

The inputs to the algorithm include the database of geospatial threats, the (possibly uncertain) 4-D trajectory; the client-specified thresholds for minimum acceptable distances above, below, and aside each type of threat; and the client-specified minimum confidence interval to down-select the possible trajectories.

The confidence level bounds the uncertainty in the trajectories as illustrated in Figure 1. As the desired confidence level increases, the probability of the trajectories considered decreases, i.e., many more possible trajectories are considered for a 95% confidence level, even if they are not very likely to occur than for the significantly lower 25% confidence level, which considers only the most likely trajectories. The confidence level corresponds to the level of risk the client is willing to accept. A confidence level does not need to be specified for a certain path.

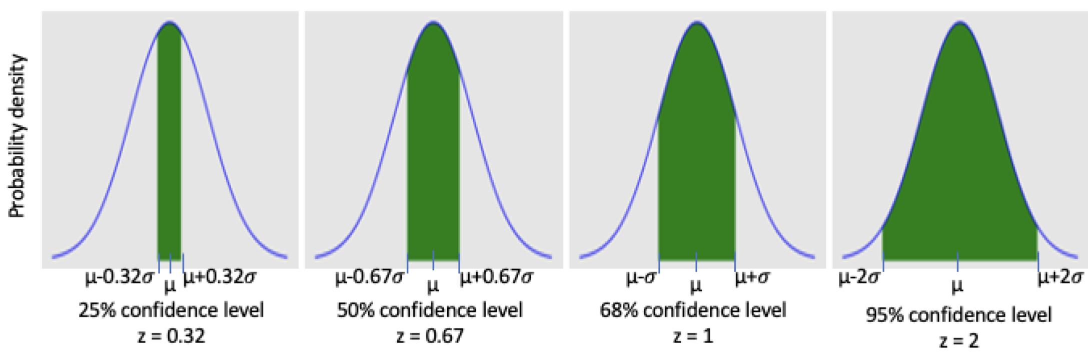

Figure 1.—The trajectories considered, for example, client-specified confidence levels, are shown in the green section of the Gaussian density. As the desired confidence level increases, the range of trajectories also includes those with a lower probability of occurring. Although we illustrate the concept of confidence level to trajectories considered with a univariate Gaussian density for a single variable, such as latitude, the concept equally applies to a multivariate Gaussian density over two (position denoted by latitude and longitude) or three (position denoted by latitude and longitude and altitude) variables.

The outputs from the algorithm are the points along the trajectory where proximity falls below the threat-applicable client-specified threshold. For each such point, the nearest approach points (i.e., points along the trajectory where proximity is smallest), the distance to the nearest approach

*Position can be represented using projected, i.e., `(easting, northing)`, or geographic, i.e., `(latitude, longitude)`, coordinates.

point, and the *severity of violation* are also computed. The severity of the violation is determined by the safety margin (SM) remaining and is computed using the percent error formula

$$\mathrm{SM} = \frac{distance - threshold}{threshold} \times 100. \tag{1}$$

Examples of safety margin (SM) are illustrated in Figure 2.

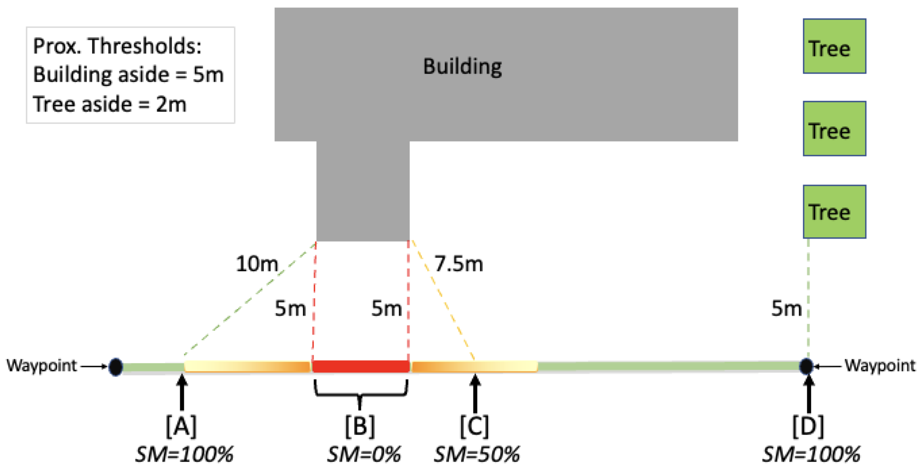

Figure 2.—Method for interpreting SM from a threat. SM is capped at 100%, meaning the path is at least twice as far from the obstacle as the minimum client-specified distance. All trajectory points in this illustration that are left of trajectory point [A] are at least 10m from the building and thus have 100% margin. 0% SM means no safety margin remains; the path is at or closer to the threat than the specified distance. All trajectory points on the flight path delimited within range [B] are 5m from the building and thus have 0% SM beyond the specified distance threshold. Finally, an SM between 0% and 100% means there is that much margin above the specified distance threshold. In the example shown, when the drone is at trajectory point [C], it is 7.5m from the building, which is 2.5m, or 50%, farther than the "Building aside" specified threshold. Note that thresholds are specific to a threat type. For example, when the drone is at trajectory point [D], it is 5m from the nearest threat, which is 150% farther than the required 2m from a tree threat, resulting in a (capped) 100% SM. SM is computed for each trajectory point along a flight path, regardless of direction from which that point is approached. (Not to scale.)

The PtT algorithm computes the available SM for each trajectory point against each threat in the database. It does this separately for altitude and for 2-D position. We begin with the description of the position SM algorithm, but it may be computationally more efficient to reverse the order in practice, for instance, for flight operations that are typically well above the majority of threats in the database.

To determine available SM of the position from threats, PtT begins by checking whether the mean value of the trajectory point is inside the threat. If it is, there is no safety margin remaining, and, thus, SM is set to zero, meaning the path is at or closer to the threat than the specified distance. For display purposes, the closest distance is set to zero and the closest position is the trajectory point.

Otherwise, the trajectory point is outside the threat, and SM is computed. It first computes the distance from the mean value of the trajectory point to the closest point on the edge of the threat (polygon). If the trajectory is certain, this distance and location are the final results used in the SM computation. Alternately, if the exact trajectory is uncertain, the level of risk the client is willing to accept determines the range of trajectories to be considered.

As mentioned above, the uncertainty in the trajectory is represented by a multivariate Gaussian distribution, such as shown in the top plot of Figure 3. The isocontours of a multivariate Gaussian is an axis-aligned ellipse, such as the projection of the distribution shown in the bottom plot of Figure 3, with the center at the mean, the x-axis of length $2r_1$ and the y-axis of length $2r_2$, where r_1 and r_2 are defined as follows[†]:

$$r_1 = \sqrt{2\sigma_1^2 \log(\frac{1}{2\pi c \sigma_1 \sigma_2})} \tag{2}$$

and

$$r_2 = \sqrt{2\sigma_2^2 \log(\frac{1}{2\pi c \sigma_1 \sigma_2})}, \tag{3}$$

where constant

$$c = \frac{1}{e}(\frac{1}{2\pi \sigma_1 \sigma_2}) \tag{4}$$

determines the fraction of peak height of the Gaussian density.

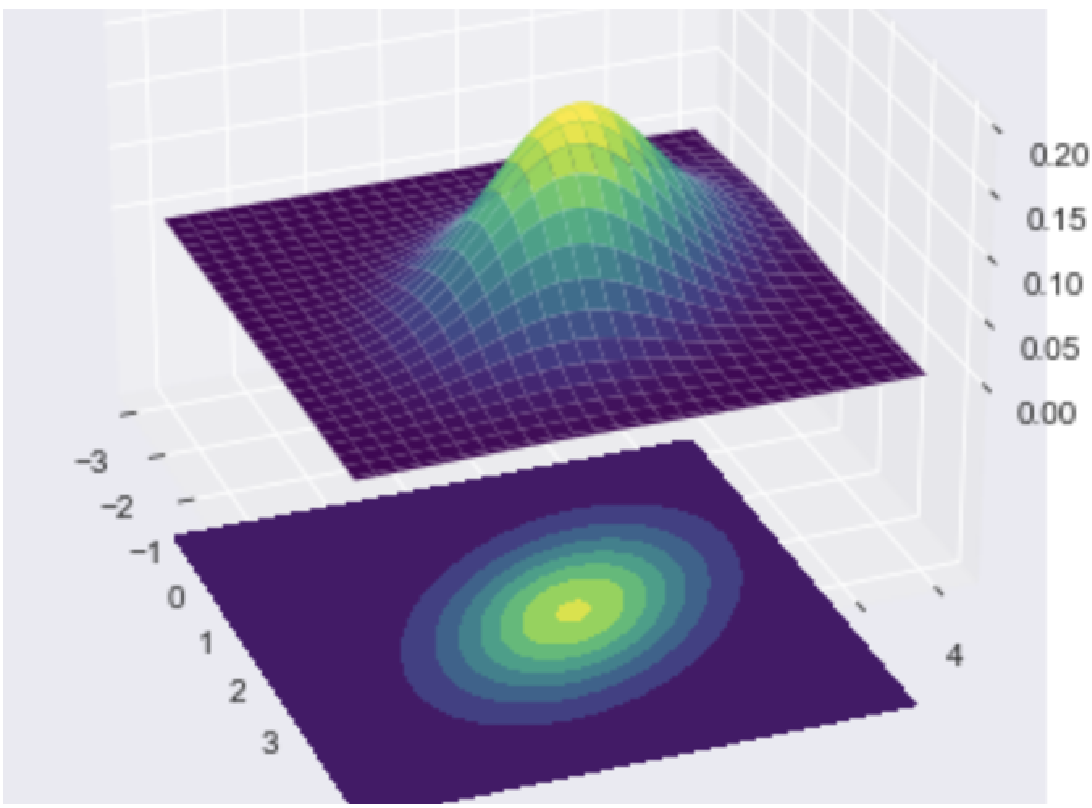

Figure 3.—An example Gaussian density over two variables, such as latitude and longitude, shown on top of the projected contour.

[†]http://cs229.stanford.edu/section/gaussians.pdf (Section 4.1)

The client-specified confidence level is used to determine the isocontour that bounds the possible trajectories within the client's level of risk. To determine the desired trajectory uncertainty ellipse, we compute the Z score. The Z score can be observed as a location in a distribution[‡], particularly, the fraction of the peak height of the Gaussian density in each dimension, and is computed as $Z = (x - \mu)/\sigma$ where μ is the mean and σ is the standard deviation of the position. For example, if a low confidence level is specified, the resulting ellipse may be the small yellow or lighter green ellipses shown in the projected contour in Figure 3. Alternatively, if a high confidence level is specified, the resulting ellipse may be one of the wider blue ellipses. The lengths of the ellipse axes are determined using the equations above for r_1 and r_2, at which the constant c is equal to the Z score.

Once the desired ellipse is determined, the shortest distance from the threat can be computed. First, a line is drawn that connects the trajectory mean and the closest point on the threat found as described above for a specific trajectory. The shortest distance is the smaller of the distance from one of the two points where the line intersects the ellipse, as shown in Figure 4. If the threat is small enough to fit within the ellipse of a chosen Z score or there is an overlap between the threat and the selected ellipse, then the SM is set to 0% out of an abundance of caution.

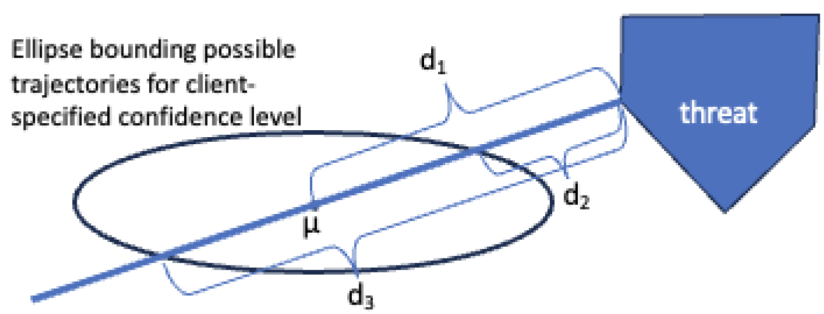

Figure 4.—The distance along an uncertain trajectory and a threat is the lesser of d_2 or d_3. d_1 is the distance from the trajectory mean point to a point on the nearest edge of the threat, while d_2 and d_3 are the two points where a line that goes through the mean to the edge intersects the uncertainty ellipse. The ellipse bounds the possible trajectories for the client-specified confidence level.

We have a SM for the horizontal distance from each threat at this stage. Computing the vertical SM is simpler because vertical position is a univariate Gaussian density. For further simplification, once the distribution is bounded by the client-specified confidence level, we base the vertical SM on only the endpoint of the altitude uncertainty interval closest to the threat polygon. This is equivalent to using the closer of the two ellipse-line intersection points, as described in Figure 4. We show only this endpoint in Figure 5. The final SM is then determined based on horizontal and vertical SMs.

We consider the following four cases, corresponding to the numbered trajectory points in Figure 5:

1. Case 1: The trajectory is horizontally well-separated from the threat, i.e., the horizontal SM

[‡]https://www.ztable.net/z-score/

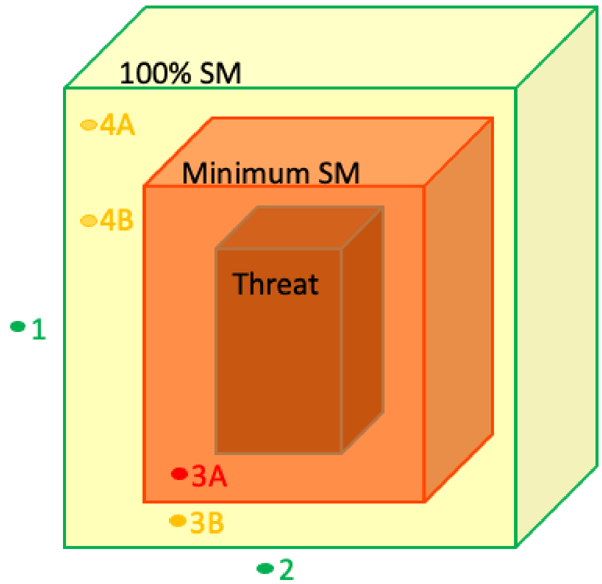

Figure 5.—Multiple cases for computing overall SM based on individual horizontal SM and vertical SM. The threat polygon is extended by the horizontal and vertical proximity threshold distances to define the *Minimum SM* polygon. Any trajectory points inside that polygon have 0% SM. Any points beyond the 100% SM polygon, meaning they are more than twice as far as the required horizontal or vertical proximity threshold distances, have 100% SM. SM for the remaining points is determined as explained in the text.

is 100%, meaning the point lies outside the *100% SM* polygon shown in Figure 5. The altitude is irrelevant and is therefore not computed. The final SM for that threat remains at 100%.

2. Case 2: The trajectory is vertically well-separated from the threat, i.e., the vertical SM, computed using Equation 1, is 100%, again meaning the point lies outside the *100% SM* polygon shown in Figure 5. The horizontal distance is now irrelevant. The final SM for that threat is 100%.

3. Case 3: The trajectory is closer to the threat than the client-specified horizontal proximity threshold. The horizontal SM is therefore 0%. The final SM is equal to the vertical SM, computed using Equation 1. This case is illustrated by the trajectory points labeled 3A and 3B. Point 3A is between the vertical elevations of the threat extended by the client-specified vertical proximity threshold distance, i.e., inside the *Minimum SM* polygon shown in Figure 5. Its vertical SM, and thus the final SM, is 0%. In contrast, point 3B is outside the vertical dimensions of the *Minimum SM* polygon. Its final SM is between 0% and 100%, as computed by Equation 1. Note that case 2 is a subset of this case and is handled separately only for computational efficiency.

4. Case 4: The trajectory is at least minimally horizontally separated from the threat, with the horizontal SM between 0% and 100%. The vertical SM may be either 0% (point 4B), lying inside the *vertical* extent of the *Minimum SM* polygon, or between 0% and 100% (point 4A), as computed using Equation 1. [Case 2 already addressed a vertical SM of greater than 100%. Case 1 is a subset of this case and is handled separately only for coputational efficiency.] If

the vertical SM is 0% (e.g., for point 4B), the final SM is set to the horizontal SM. Otherwise, e.g., for point 4A, the final SM is set to the *larger* of the horizontal SM or vertical SM. As an example of why we select the larger margin, imagine a flight with a trajectory parallel to the top of the threat with a vertical SM of 10% that is currently more than twice as far horizontally as it needs to be. It has horizontal and final SM of 100%. As the flight approaches the threat, its horizontal SM decreases. As it reaches the horizontal boundary of the *Minimum SM* polygon, its horizontal SM becomes 0%. However, because it is still 10% above the required vertical threshold distance, it still has margin beyond the required separation thresholds, albeit a small 10% margin in this case.

PtT is computed for each point on the trajectory and recomputed when either the trajectory or the threat database is updated. Each of the computed parameters is available for display to the client. Which parameters should be displayed on a dashboard versus an initially hidden display will vary based on client needs, available display real estate, and additional information to be displayed. In the next section, we describe how the PtT metric was implemented onboard a drone to alert ground operators of threats and show how threats were displayed for a human-in-the-loop (HITL) usability study of an example Urban Air Mobility (UAM) service provider.

3 Usage Examples

The Proximity to Threat (PtT) function was tested in two locations as part of technology development projects: the Air Traffic Management eXploration (ATM-X) project (Ref. 1, 6) which simulated flights around Dallas, TX, and the System Wide Safety (SWS) project which flew drones as well as simulated aircraft around a fictitious city named City Environment for Range Testing of Autonomous Integrated Navigation (CERTAIN). In this section, we describe testing of PtT as part of testing conducted at the CERTAIN range in support of the SWS project within NASA's Aeronautics Research Mission Directorate (ARMD) (Ref. 7, 8).

NASA Langley Research Center (LaRC)'s CERTAIN area uses LaRC airspace below 400 ft above ground level (AGL) to facilitate small Unmanned Aircraft Systems (sUAS) technology research (Ref. 9). The range is subdivided into four areas; some areas are sparsely populated, while others are more urban and resemble an industrial park or college campus with a more concentrated population, many buildings, parking lots, pedestrian areas, and trees. An example of the fictitious city model is shown in Figure 6.

The location-specific threat database used for PtT was populated with polygons describing the buildings, trees, and poles (e.g., light poles); this initial database did not include abstract threats such as weather or special use airspace. A polygon described by a list of vertices for an example building is shown in Figure 7. The database entry for each polygon also included information about the bottom and top elevations of the threat.

The PtT function was implemented onboard a sUAS to detect proximity violations during flight (Ref. 10). The vehicle is a Tarot-based octocopter with two Intel-based single-board research computer systems and the COTS onboard systems. A simplified onboard version of PtT was tested on scenarios explicitly designed to result in proximity violations. Violations detected onboard were displayed on a ground station interface, as shown in Figure 8.

Also, in the SWS project, an example Supplemental Data Service Provider (SDSP).[§] The

[§]An SDSP is an entity in the Unmanned Aircraft Systems (UAS) Traffic Management (UTM) approach for manag-

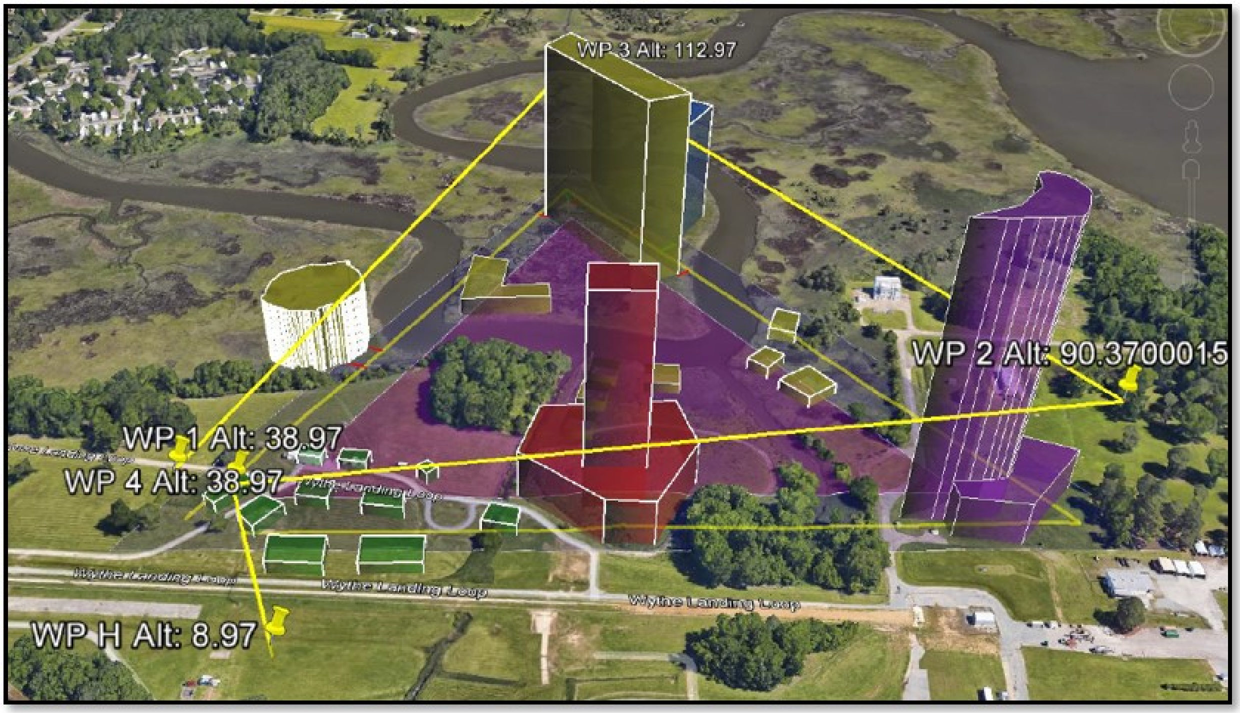

Figure 6.—Model of fictitious city used to test PtT. Shown is an isometric view of the city model loaded into Google Earth. The yellow line represents a flight trajectory. (NASA image. Maps data: Google Earth)

interfaces were tested as part of a human-in-the-loop (HITL) study with sixteen participants. PtT as one of the functions under test, and participants were asked various questions to determine the usefulness and usability of the product. An example SDSP display of PtT alerts is shown in Figure 9. Details of the study and its results are described in Feldman et al. (Ref. 12).

4 Conclusion

Emerging air mobility operations, such as air taxis or package delivery by drone, fly at low altitudes where they are more likely to encounter obstacles along discretionary routes. Even along prescribed routes, unexpected adverse weather (e.g., scattered low clouds) or operational constraints (e.g., weak GPS signal) may lead to deviations toward an unnoticed obstacle. The sustained high workload during low altitude operations in busy airspace could result in the threat being overlooked until energy-wasteful abrupt maneuvers are required or an incident or accident occurs. Furthermore, factors such as variable winds, pilot or flight control system actions, collision avoidance maneuvers, etc., inhibit predicting the flight path with certainty. In this report, we described the Proximity to Threat (PtT) function, which continuously monitors the expected flight trajectory in relation to a multitude of threats, and preemptively alerts the pilot or operator of any threats along the path that are within a client-specified distance. Because a flight's path may be affected by a variety of factors, such as inaccurate forecasts or unexpected aircraft performance, the expected trajectory

ing the high volume of traffic expected for Urban Air Mobility (UAM) and Low Altitude Mobility (LAM) operations. These third-party entities provide essential or enhanced flight-relevant terrain and obstacle data, specialized weather data, surveillance, operational constraints, performance, among others (Ref. 11).

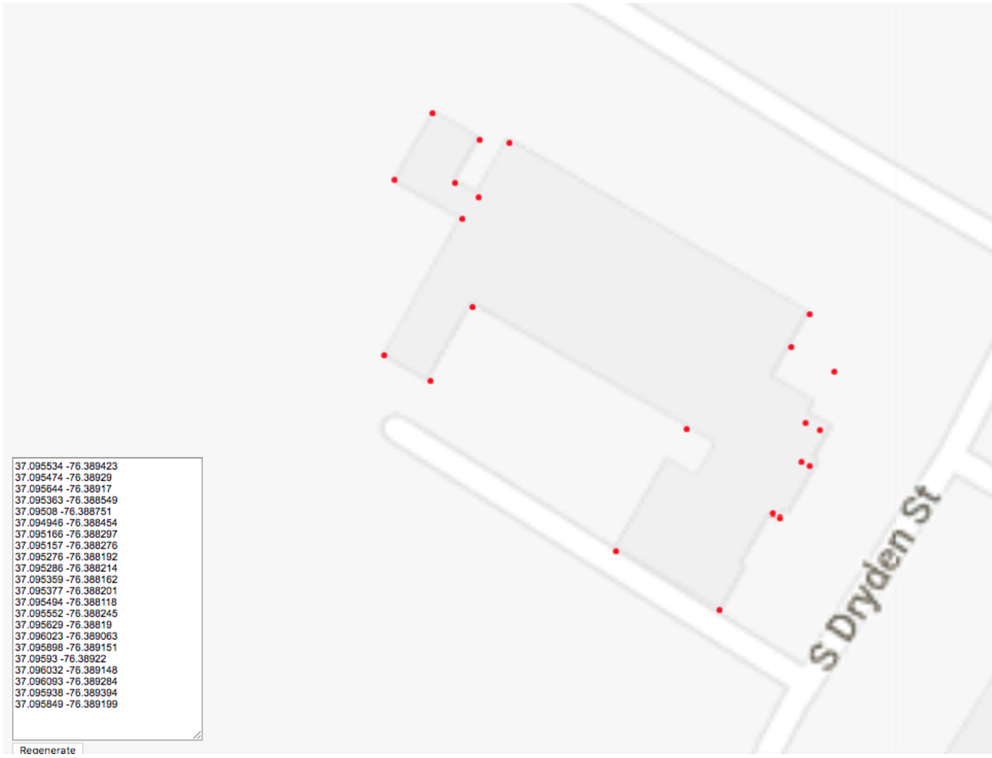

Figure 7.—Latitude and longitude coordinates for the vertices (red dots) describing a building on the CERTAIN range. [Note the discrepancy between the actual perimeter (gray outline) and the encoding polygon due to inaccurate sensing. In later database revisions, polygons were updated using a more accurate LiDAR remote sensing method.] (NASA image)

is represented as a Gaussian distribution and the client can provide an uncertainty confidence level to specify an acceptable level of risk. Finally, we presented usage examples of the function running onboard a small Unmanned Aircraft Systems (sUAS) to detect threats along the flight path, displaying detected threats on a ground station display, as well as an example of a NASA-developed service provider display that was evaluated as part of a human-in-the-loop (HITL) usability study.

In future work, the onboard implementation will be extended to include abstract threats, such as Temporary Flight Restrictions (TFRs), account for trajectory uncertainty, and explore additional user interface design options. Additionally, although we have only described using PtT as a part of a route planning *operator* support system, it can also be used to inform automated route replanning.

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Figure 8.—PtT function tested onboard an octocopter flying over CERTAIN fictional city. The flight route is the yellow line, the vehicle is the white symbol toward the bottom of the image, and the red line extending from the vehicle to a building shows a proximity violation. Although PtT produces an alert for every trajectory point that violates the client-specified thresholds, only a single red line depicting the nearest alert is shown on this image to save bandwidth. (NASA image. Maps Data: Open Street Maps)

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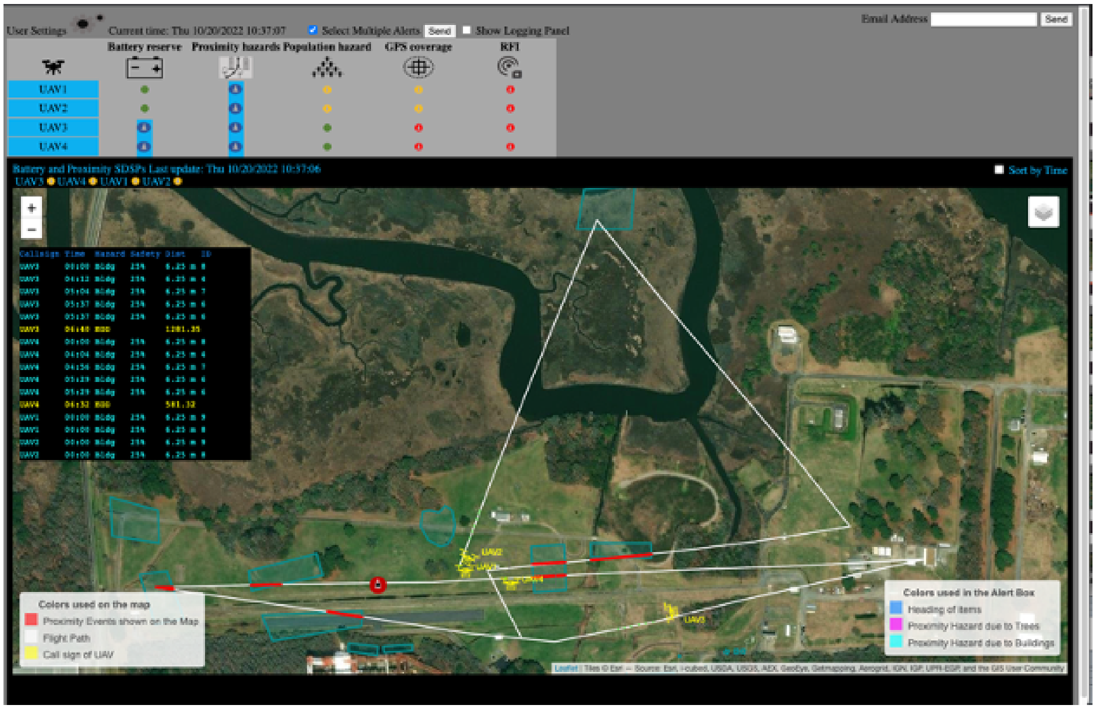

Figure 9.—The usability and usefulness of the PtT function was evaluated in a HITL study, using example displays similar to this one. Red segments show locations where the flight path is closer than a client-specified distance to a building. (NASA image. Maps Data: Google, Image ©2023 Landsat/Copernicus)

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