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Impact of Sensors on Collision Risk Prediction for Non-Cooperative Traffic in Terminal Airspace

C.H. John Wang, Shi Kun Tan
Air Traffic Management Research Institute
Nanyang Technological University
65 Nanyang Drive, Singapore 637460

Lynette Koay Jie Ting, and Kin Huat Low§
School of Mechanical and Aerospace Engineering
Nanyang Technological University
50 Nanyang Avenue, Singapore 639798
§ Corresponding Author: mkhlow@ntu.edu.sg

***Abstract*—The availability of off the shelf, easy to control, unmanned aerial systems (UAS) on the market has led to an increase in report of UAS incursion into terminal airspace. Such incursions often lead to airport shutdowns due to safety concern and could cause a cascading disruption to airline operations throughout the region. A better assessment tool for the collision risk between the existing air traffic and the intruder could help reduce unnecessary disruption to air traffic operations. Work has been done on the assessment of such risk using probabilistic UAS positions prediction based on Monte-Carlo simulations, under the assumption of a non-cooperative intruder with worst-case intention aiming at the flight corridor. Alert areas around the runway and the aircraft flight path could be constructed using the collision prediction method, albeit only valid under specific conditions. The accuracy of the predictions could be further improved with the incorporation of ground-based tracking equipment. This paper looks into how the availability of UAS tracking information could be used to complement the collision prediction algorithm, and how its inclusion affects the collision risk assessment.**

List of Abbreviations

ACAS	Airborne Collision Avoidance System
AGL	Above Ground Level
CA	Collision Alert
CPA	Closest Point of Approach
DMOD	Distance Modifier
RA	Resolution Advisory
TA	Traffic Advisory
TCAS	Traffic Alert and Collision Avoidance System
UAS	Unmanned Aerial Systems

I. Introduction

The rapid development of recreational multi-copter in recent years has put more of these unmanned aerial systems (UAS) in the hand of the masses. These UAS, like the remote controlled (RC) aircraft from the previous generations, does not require the pilot to obtain a license to operate; unlike the RC aircraft, though, the multi-copter is both cheaper in cost and easier to operate. As a result of the influx of inexperienced UAS operators, a raising number of UAS incursion into the restricted airspace around airports has been reported. Due to the possible safety hazard posed by a collision between the UAS and low-flying aircraft operating within the aerodrome, these incursion would often lead to airport shutdowns for long period of time. These shutdowns could last anywhere between tens of minutes to a few hours as seen in recent incidents [1]–[3], with knock-on effect on scheduling disruption lasting for hours afterward.

The prevention of unintentional incursion into controlled airspace by recreational UAS operators could be achieved by the implementation of global positioning system (GPS) based geofencing within the UAS flight computer, as is the case for manufacturers such as DJI. However, geofencing would not work if the UAS does not have the protected area in its database, either due to the lack of such feature on the flight controller or malfunctioning flight software. As there would be no way for the air traffic controller to interact and coordinate with the intruding UAS, it would have to be treated as non-cooperative traffic.

Without a reliable method to safely remove the intruder before it became a problem, the aim of the collision prevention algorithm would then be concentrated on ensuring the safety of the aircraft already in the controlled airspace for the duration needed to complete their takeoff or landing operations. The goal for this study is to establish alert zones surrounding the runway using collision risk assessment, and investigate the effect of the availability of UAS tracking information on these assessment.

II. Literature Review

Collision prevention in airspace is generally handled by the air traffic controllers well in advance of a possible conflict through the usage of ADS-B transponder data, which are collected using the secondary surveillance radar with an update rate of no greater than 3 seconds [4]. An additional fail-safe for collision prevention is through the ACAS system which utilizes a specialized transponder that provides warning and required action to resolve the conflict in a pair-wise fashion at 1 second interval [5]. The transponder systems, broadcasting the position and velocity of the aircraft every few seconds, allowed the air traffic management system to quickly detect possible conflict and generate the necessary action for its resolution. However, such constant flow of data will not be available for non-cooperative intruders without the installation of ground-based primary sensors.

Ground-based detection of intruding UAS could be accomplished using a number of active and passive detection technologies. Active detection of UAS is generally achieved using Pulse-Doppler radar, while the passive detection technologies utilizes some form of receiver to capture the energy reflection/emission from the UAS, e.g. visible light or IR camera, radio spectrum sensor, or acoustic sensor. Some of the detection methods are more susceptible to environmental conditions or ambient noise than others, such as camera under raining conditions or acoustic sensor during high traffic period, thus limiting its effective detection range. Of the eight systems surveyed in a 2016 Massachusetts Department of Transportation review [6], only four of those were capable of covering the 5 km controlled airspace surrounding the runway. The four systems with sufficient range utilizes either radar technology or radio-frequency (RF) spectrum sensor.

Without the UAS detecting equipment, the information available to the air traffic controller on the intruding UAS in terminal airspace can be very limited. It might consist of only the estimated flight performance of the UAS (based on the type of UAS e.g. recreational UAS or payload capable commercial UAS) and the position of its initial incursion from sighting reports. The collision risk assessment could be calculated either based on the estimated closest point of approach (CPA) a la the ACAS system [5] or the collision prevention system used in UAS traffic avoidance algorithm [7], [8]. The margin of error in UAS collision forecast is expected to be quite high due to uncertainties in initial position and estimated flight performance of the UAS. The margin of error could be reduced through the availability of tracking sensors.

In a way, the modeling of the collision risk could be viewed as an extension of the UAS detect-and-avoid (DAA) research [7], which is rooted in the research done for the airborne collision avoidance system (ACAS) developed for civil aviation traffic [9]. In general, airborne traffic collision avoidance includes the following components: detection of traffic, propagation of states, detection of conflict, and resolution of the conflict [10]. In this study, the detection of traffic would depends on the availability of UAS tracking sensors, while the simulation tool performs the propagation of states, i.e. path prediction, and detection of conflict. The resolution of conflict is not in the scope of this study.

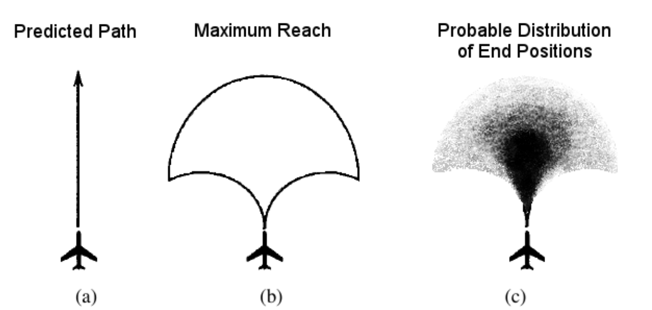


Fig. 1. Common trajectory prediction methods: (a) Nominal, (b) Worst-Case, and (c) Probabilistic methods. Based on [7] .

The prediction of possible aircraft's future position is generally conducted through three different methods in ACAS related research, illustrated in Fig. 1: the nominal (intention) based prediction, the worst-case (maximum range) based prediction, and the probabilistic based prediction [9], [10]. The nominal method predict the aircraft trajectory using the available flight information from both party in the traffic collision assessment; the worst-case method employs the possible intersection of trajectories using the maximum range of motion for the two aircraft; the probabilistic method is further split into three types: predicting the trajectory by supplementing the deterministic aircraft trajectory with probability distribution function [11]–[13]; by tallying results from Monte Carlo simulation using aircraft performance information and known initial position [9]; or by a combination of both by continuously updating the initial conditions for the Monte-Carlo simulation as new sensor data becomes available [8], [14].

For a prediction system based on the ACAS framework, the prediction of possible collision is calculated using the closest point of approach (CPA) between the predicted trajectories of the two aircraft in question [5]. In the case where probabilistic path prediction was used, on the other hand, the collision chance is assessed by calculating the overlap between the probable spatial distribution of the UAS and the alert regions surrounding the aircraft [9].

In the case where no tracking information is available on the intruding UAS, path prediction would not be possible using the nominal method and the deterministic approach. The usage of maximum UAS reach was also ruled out due to high maneuverability of the multi-copter system. The UAS path prediction thus depends on the Monte-Carlo simulation.

III. Simulation Strategies

The simulation algorithm for UAS path prediction for the current study is an adaptation of the code used in the previous assessment for collision risk of non-cooperative intruding UAS. Instead of using only the initial position of the UAS and simulate over the duration of which it might be a safety hazard, a 20 seconds collision assessment is run for each update in UAS position and velocity. Two different path prediction methods were used in the current study, both of which were based on the Monte-Carlo solver developed from our previous study. The first method assumes that the UAS intend to follow the current direction of travel; the other assumes the worst-case intention where the UAS will be accelerating towards the flight corridor. The following sections gives an overview of the path prediction and collision prediction code used in this study.

A. Path Prediction

Monte-Carlo simulation utilizes a large number of random samples to obtain the probability distribution for the possible outcomes. In this case, a randomization function was applied to the thrust vector of the UAS, while the sample UAS path is defined using a combination of the randomized thrust vector and the flight characteristics of the UAS. A simplified equation of motion for the UAS, including the randomization function, is shown in (1).

$$\boldsymbol{a} = \frac{d\boldsymbol{V}}{dt} = \frac{\mathrm{rand}() \times (\boldsymbol{T_{max}} - m\boldsymbol{g} - K_d \boldsymbol{V^2})}{m} \qquad (1)$$

The acceleration available to the UAS at each time step was evaluated using the maximum thrust of the UAS (T_{max}), the mass of the UAS (m), and the drag force acting on the UAS based on its airspeed ($K_d \boldsymbol{V^2}$). The performance data for the current study is based on the DJI Inspire 2 (Table I, with the maximum thrust based on the maximum take-off weight, the mass based on the minimally viable take-off weight, and the drag constant calculated using $T_{max} = K_d V_{max}^2$.

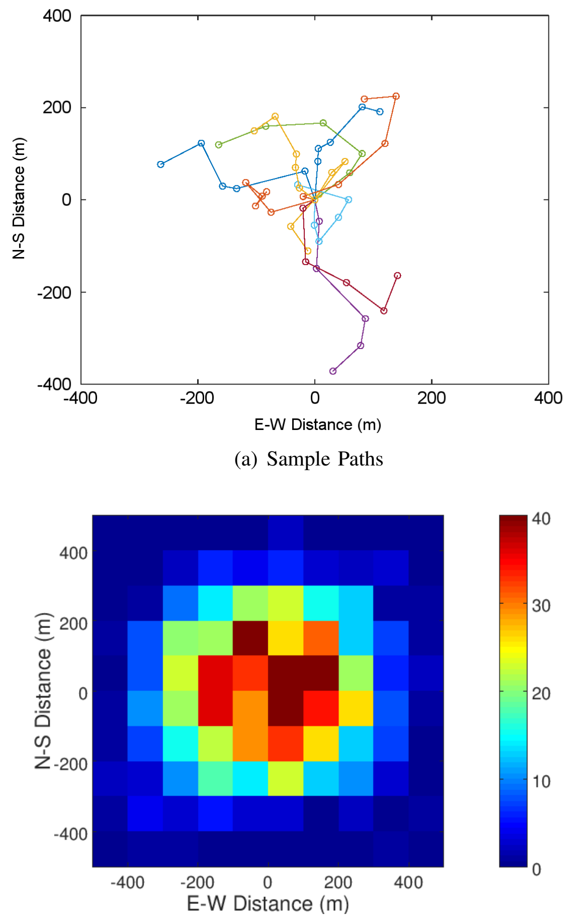
TABLE I
PERFORMANCE SPECIFICATIONS OF DJI INSPIRE 2, FROM REF. [15]

Variable	Value
Maximum Thrust (T_{max})	4 kgf
UAS Mass (m)	3.4 kg
Maximum Speed (V_{max})	26 m/s

For each time step of the simulation, the maximum available thrust is multiplied by a randomization function to obtain the thrust force and direction that would be applied to the UAS. In the case of multi-rotor UAS, however, the flight performance of the hardware puts very little limit on the range of possible motion of the UAS comparing to its maximum flight range, and the UAS has an equal probability of change in headings towards any directions. As a result, the application of an uniform random number generator for the UAS path prediction resulted in a normal distribution of the UAS position at the end of simulation, with the mean value offset from the initial start point depending on the initial UAS velocity. Monte-Carlo simulation was conducted using the initial position of the UAS as input and randomized velocity vector at each time step to obtain the distribution of possible final UAS position. Sample paths from the simulation and the resulting probabilistic distribution graphs are shown in Fig. 2.

Based on the Monte-Carlo results, $> 90\%$ of the simulated UAS ended up within 350 meters from the starting position after 100 seconds. The area covered by the 90% confidence ellipse of the final distribution is small comparing to the area covering all possible UAS end position, which has a radius of 2,000 meters based on the maximum range of the UAS. The simulation results using the uniform random number generator for thrust vector at each time step would therefore not be useful for collision risk assessment within terminal airspace without imposing additional constrain on the UAS. One way to achieve this is to include an intent information into the simulation.

The randomization function could be modified to incorporate the intent of the UAS, i.e. the uniform random function for UAS with no specific intention or random function with normal distribution with the mean reflecting the intended magnitude and direction. In the case of normal distribution, the distribution function is truncated by the physical limit of the UAS and the variance of the function would reflect the resolve of the UAS to stay in the direction of intended travel. The effect of intent information on the final UAS distribution is illustrated in the example shown in Fig. 3, with simulations conducted with 2000 samples: The simulation without intent information utilized the uniform random function, while the simulation with intent information utilized a truncated normal distribution with the mean value of maximum thrust bearing 0 degree and a variance of 1.



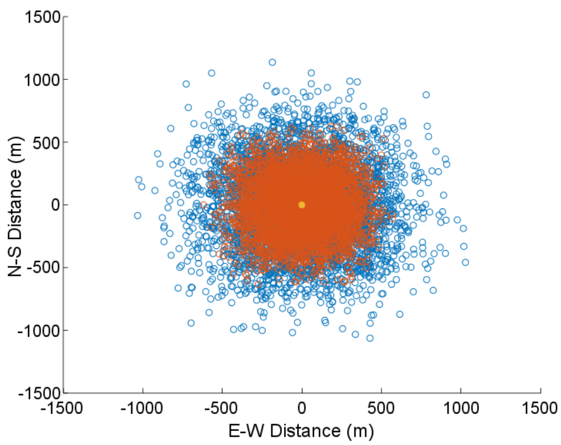
(a) Sample Paths

(b) Histogram

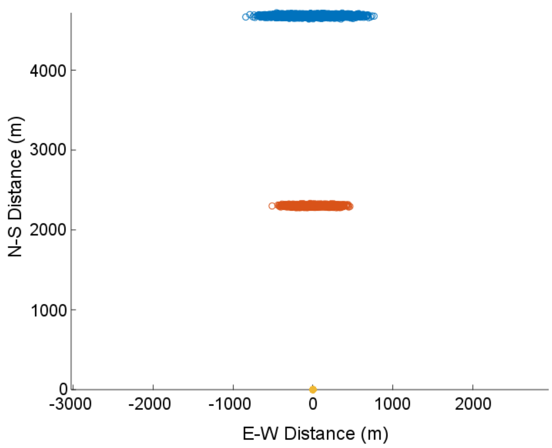
Fig. 2. Path prediction using the uniform-random algorithm showing (a) sample paths and (b) histogram from 1000 samples using Monte-Carlo simulation. Simulation time of 100 seconds and V_{max} of 20 m/s was used.

The simulation results from Fig. 3 demonstrated the importance of including intent information in path prediction for multi-rotor type UAS. For such highly agile UAS with little to no limitation on turning radius, the lack of an intended direction of travel would lead to the UAS zigzagging around its initial position. The resulting final UAS position prediction would be a 2 dimensional normal distribution with the mean at the point of origin and the variance increase with time, as shown in Fig. 3(a). Using this simulation method, the percentage of samples that could lead to meaningful collision risk estimation would be very small, making it not an ideal tool in collision risk prediction.

The increase in variance was also observed in the results for the case with intent information as the probabilistic distribution flattens over time. The change in distribution of UAS position resembles the distribution based on tracking uncertainty shown in [14] and [11], though with larger variation



(a) Without intent information



(b) With intent information

Fig. 3. Projected position of the UAS as it spread out over time, using (a) the uniform-random algorithm (without intent information) and (b) the normal distribution with variance of 1, i.e. with intent information. The symbols are: initial UAS position (solid yellow circle), 100 seconds predictions (orange circle), and 200 seconds predictions(blue circle) using 2000 samples.

in the E-W direction which is likely due to the difference in turn rate between passenger aircraft and multi-rotor UAS. The mean range of the UAS from the Monte-Carlo simulation is 4680 meters, which is 10% shorter than the absolute maximum range of the UAS (5200 meters) as calculated using its maximum speed.

B. Collision Prediction

Collision risk management under the ACAS framework is done through a layered approach that generally consisted of a Caution zone for Traffic Advisory (TA), a smaller Warning zone for Resolution Advisory (RA), and a final Collision Alert zone (CA) surround the passenger aircraft. For aircraft operating within 1000 feet above ground level (AGL), the system foregoes the Warning zone and the issuance of RA as the aircraft are traveling at a slower speed and under visual flight rules. The inner most layer for collision warning, the Collision Area, is the minimum separation that should be observed between two aircraft regardless of direction and speed of travel; this separation distance, called DMOD in ACAS II, is 0.3 nautical miles from the center of the host aircraft. The Caution zone for Traffic Advisory alert is defined by a time modifier of 20 seconds for < 1000 ft AGL, i.e. a breach of CA zone is expected in 20 seconds given the existing closing range between the aircraft. Using similar concept, the top-down view of the horizontal alert area used for collision prediction in the current study is illustrated in Fig. 4.

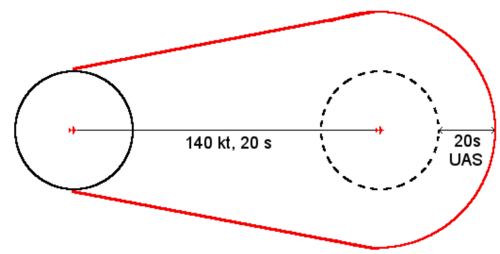


Fig. 4. Traffic advisory zone (red lines) and the collision zone (solid black circle) of an aircraft.

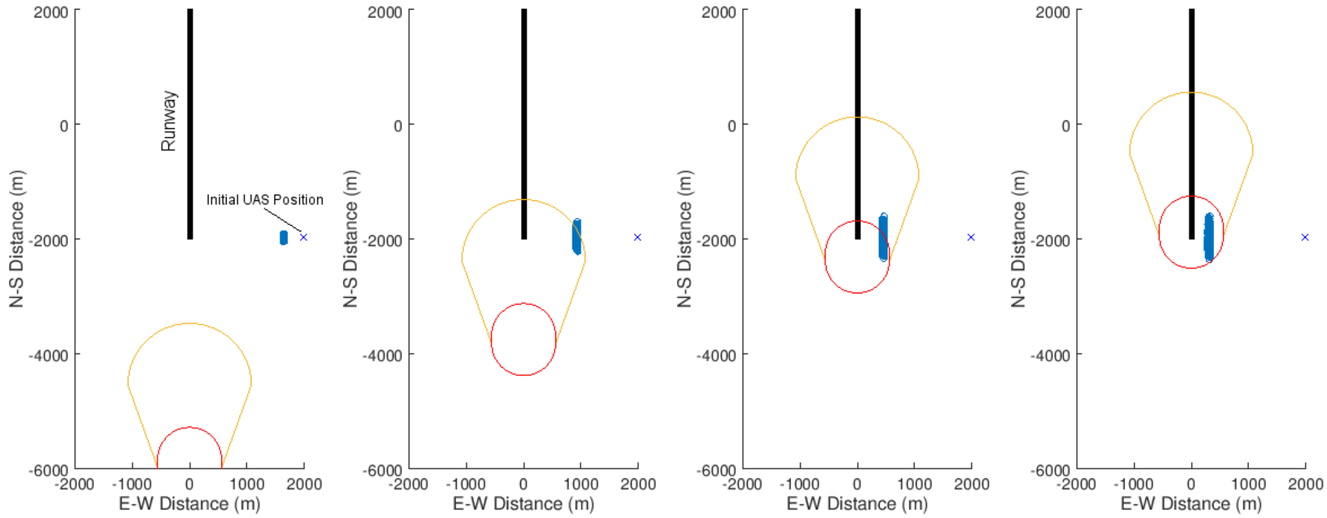
In terms of collision alert area in the vertical direction, the altitude separation threshold within ACAS II framework for aircraft operating under most circumstances is 850 feet. For the purpose of UAS collision risk assessment, the alert zone could be represented by extruding the horizontal alert area from the ground upward, or by collapsing the collision prediction into a 2D problem. The collision prediction could then be conducted by counting the Monte-Carlo generated UAS final positions that fall within the relevant alert area surrounding the aircraft. An example of the collision assessment is shown in Fig. 5.

Commercial aircraft operating within the terminal airspace generally follow a fixed path with little deviation, as observed in previous measurement of landing track in St. Louis International Airport [16] and Chicago and Atlanta Airport [17]; the aircraft is also equipped with transponders that would update the air traffic controller with information such as its altitude and speed. Given a typical landing speed of 140 knots, the aircraft would take around 70 seconds from entering the 5 km controlled airspace to touch down; it would take a similar amount of time for aircraft taking-off to exit the controlled airspace.

IV. Results and Discussion

A. Static and Pairwise Alert Zones

For collision risk assessment cases that does not involve the influence of ambient air flow, alert areas for UAS sighting could be established around the runway using the ground speed of the UAS and the commercial aircraft operating within the terminal airspace. While study into data-driven exclusion zone in terminal airspace have been done in the past [18], the concept of the alert areas in this study is similar to those used in the creation of TCAS alert zones, as sketched out in



(a) $t = 14$ s (b) $t = 44$ s (c) $t = 64$ s (d) $t = 70$ s

Fig. 5. A sample case showing UAS path prediction and collision prediction algorithm at (a) 14 seconds from the start of simulation when the aircraft entered into the visualization window, (b) 44 seconds, triggering collision warning with 93.7% of samples inside TA zone, (c) 64 seconds, with collision predicted with 6.25% of samples inside CA zone, and (d) 70 seconds, when the aircraft passed the runway threshold with 100% of the samples inside CA zone.

Fig. 6. These alert areas were formed using the deterministic approach and based purely on the maximum range of the UAS, thus labeled as deterministic alert zones.

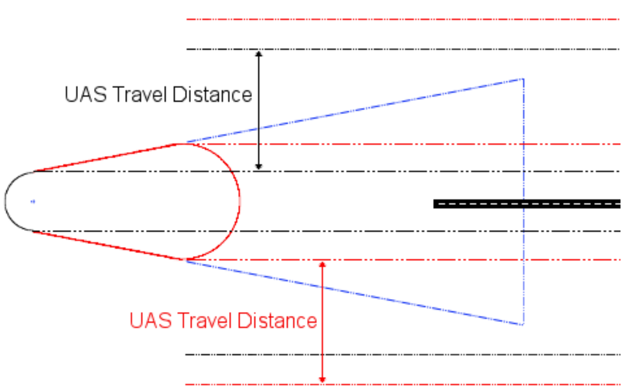


Fig. 6. Conceptual plot of the deterministic static (outer red/black dashed lines) and pairwise alert zones (blue dashed line extended from the TCAS alert zones of the aircraft) within terminal airspace. The "UAS Travel Distance" is the maximum range of the UAS over the time that the aircraft spend in the terminal airspace.

The alert zones could be further split into two types, the static alert zones (outer black and red dotted line in Fig. 6) and the pairwise alert zones (blue dotted line extended from the aircraft collision area in Fig. 6). The static alert zones were established using the maximum travel distance of the UAS towards the runway centerline over the length of simulation, typically defined by the time it takes for an aircraft operation to complete[1]. The pairwise alert zone is an extension on the TCAS protected area concept, but utilized the time it took to complete the aircraft operation instead of the fixed alert time of 20 seconds for operations under 1000 ft AGL; this alert zone changes depending on the positions of the aircraft and the UAS at the start of the simulation and would have to be established on a pairwise basis. Note that these alert zones are only valid if no other external variables, such as cross/head wind, is present.

The probabilistic, static alert zone for a 70 seconds operation, as shown in Fig. 7 was established by plotting the initial UAS position that could result in greater than 50% of the UAS samples intruding into the protected area around the take-off/landing corridor. The protected areas were established by drawing lines with offset from runway centerline by the distance of DMOD and DMOD+20 $\times$ $V_{UAS,max}$ for the CA zones (blue line) and TA zone (red line), respectively. The dotted line indicated regions without data points.

The probabilistic, pairwise alert zones were established by first creating a mesh of initial UAS position at fixed interval, then assess the collision risk between those UAS and an incoming/outgoing aircraft. The established alert zones are specific to the aircraft-UAS pair and would change with the difference between entry time of the aircraft and the initial UAS sighting time. In other words, given that the initial UAS sighting would occur at the start of simulation time, the alert zones for aircraft entering the controlled airspace 10 seconds before the start of simulation and aircraft entering 10 seconds after would be different; the amount of simulation

[1]For example, an aircraft with landing speed of 140 knots would take 70 seconds to travel from the boundary of the terminal airspace to the start of the runway.

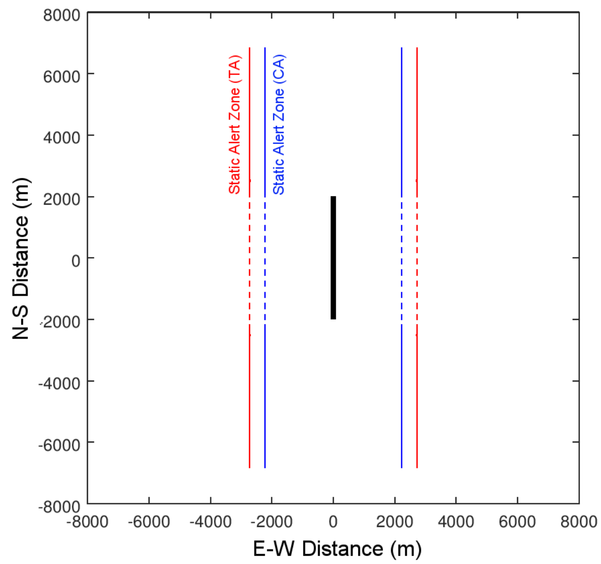


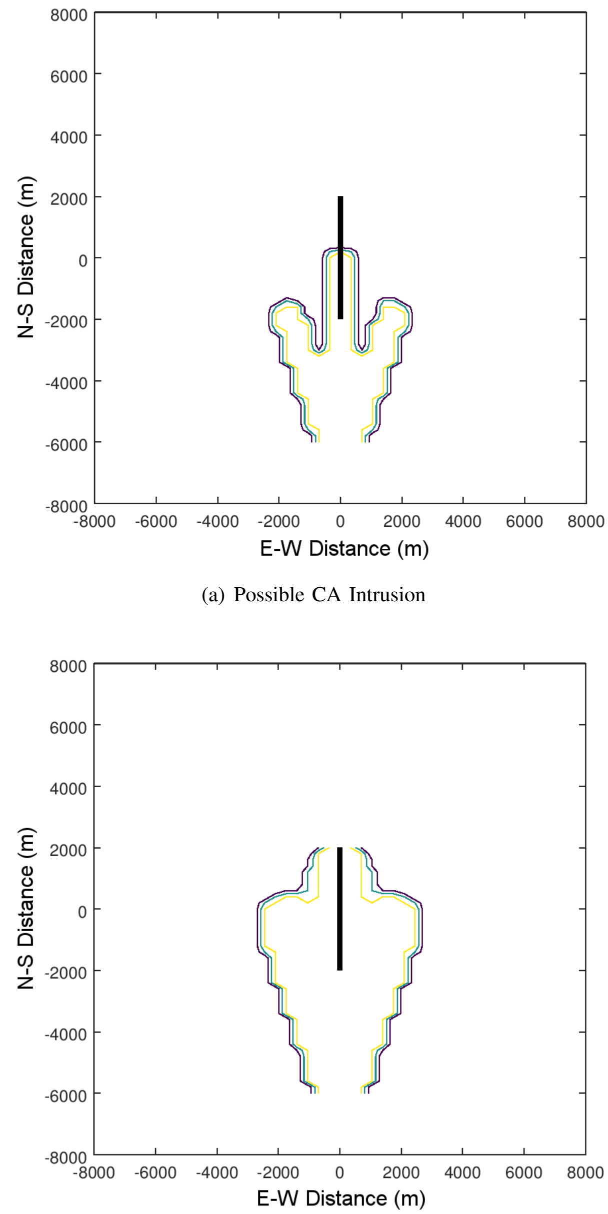
Fig. 7. Probabilistic, static traffic advisory zone (red lines) and collision zone (blue lines) for a runway. UAS with initial position inside the alert lines would pose a non-zero collision risk to existing aircraft operating in the airspace.

time required would also be different as the aircraft's time to touchdown, thus no longer at risk from UAS collision, would be different.

The pairwise alert zone shown in Fig. 8 was created using a mesh with E-W interval of 350 meters and N-S interval of 200 meters over a 70 seconds simulation period. The landing aircraft cross into the controlled airspace at the same time the UAS was initialized. The alert zones were presented as a contour plot, with the yellow line for 25% collision risk, green line for 50%, and the outer most line for 70%; as noted before an incursion event is predicted if more than 50% of the sample falls within the ACAS alert areas. The plot showed a steep increase in collision risk across the boundary of the alert zones. Due to the setup of the assessment that enforced an UAS intentions to travel at maximum speed at all time, gaps could be observed in Fig. 8(a). This is due to the code not including provisions for the UAS to slow down if it reaches the landing corridor before the aircraft is there, thus the UAS would cross the landing corridor and continue to travel beyond the CA threshold without intruding into the aircraft protected area.

B. Incorporation of UAS Tracking Data

Collision risk assessments were carried out between an commercial aircraft performing its landing operation and an UAS traveling at a fixed velocity along a fixed track. The sensor data was incorporated into the path prediction algorithm using two different methods: the worst-case intention prediction (CPA Method), which assumes that the UAS will travel at full thrust towards the flight path; and the sensor-direction retention prediction (Direction Retention Method), where UAS heading from the sensor data in conjunction with



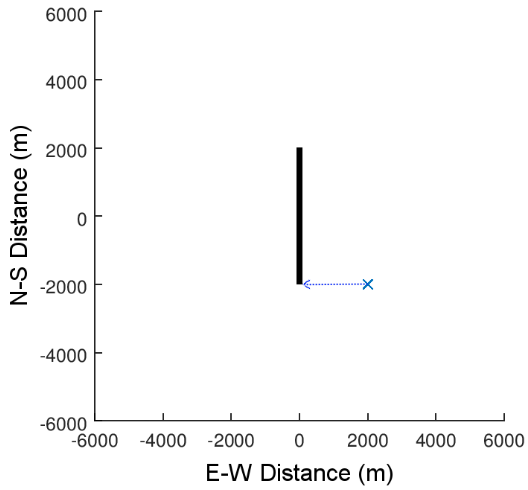
(a) Possible CA Intrusion

(b) Possible TA Warning

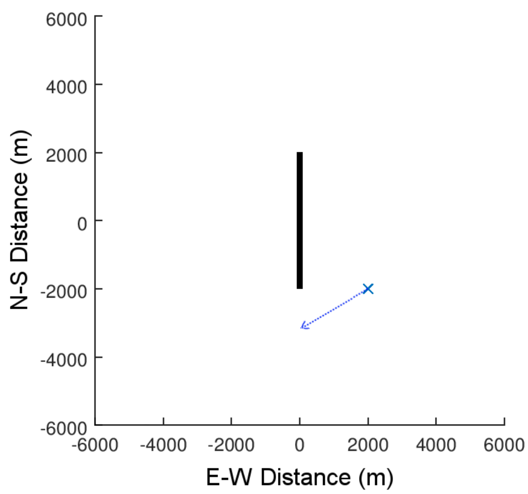
Fig. 8. Probabilistic pairwise collision assessment of initial UAS position that could lead to collision risk by intruding into (a) Collision Area and (b) Traffic Advisory area over the 70 seconds duration of the landing operation.

maximum available thrust is used. Two different tracks were employed to illustrate the difference in prediction results. The aircraft would enter into the 5 km controlled airspace at the start of the simulation, with the initial position of the UAS at 2000 m East and 2000 m South from the runway center point. The two tracks used in the assessment are shown in Fig. 9.

Track 1 is a simple straight line from the initial position of the UAS towards the runway. In this case, simulation with path prediction using intent information based on travel direction and worst-case intention would yield the same result. Track



(a) Track 1



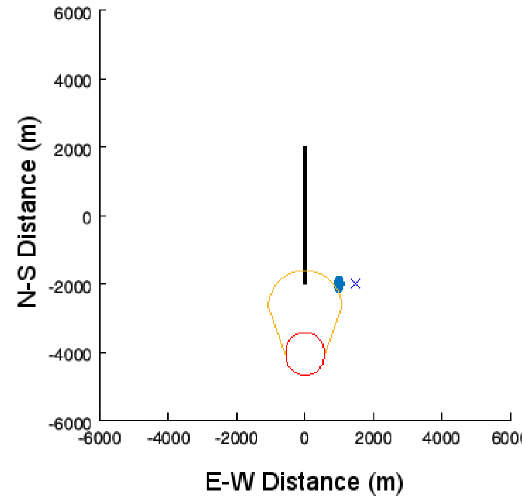
(b) Track 2

Fig. 9. Overview of the tracks taken by the intruding UAS:(a) Heading 270° at full speed, and (b) Heading 240° at full speed.

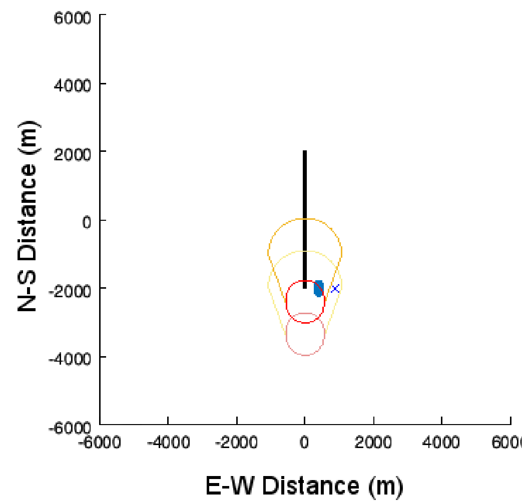
2, while also consisted of a straight line, would see the path prediction based on travel direction with a heading of 240°, while the worst-case intention would be with a heading of 270°. The UAS was set to travel along the tracks at a fixed velocity of 26 m/s.

As the initial UAS position for both of the tracks tested for this paper falls within both the static alert zone surrounding the runway and the pairwise alert zone for the incoming landing aircraft, the aircraft would be advised to abort the landing operation based on those two systems. The availability of the tracking information would enable a more accurate collision prediction and reduce the uncertainties in UAS path projection.

Track 1 is the path that the UAS in previous assessment would take, where the UAS head directly towards the landing corridor at maximum speed. Snapshots of the simulation



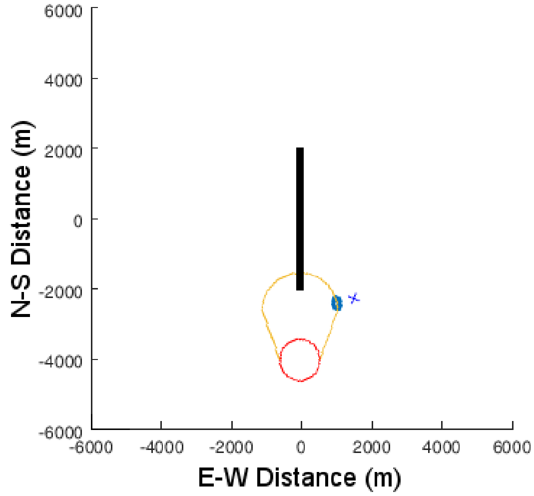
(a) $t = 20$ s



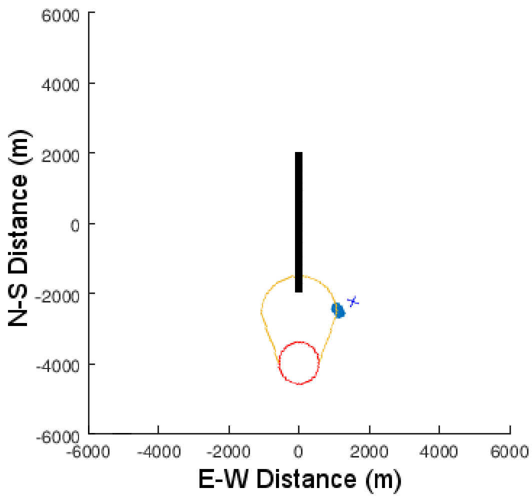
(b) $t = 43$ s

Fig. 10. Snapshots from 20 seconds UAS position projection when traveling along Track 1 that would lead to triggering of (a) TA warning (at $t = 20$ s) and (b) CA warning (at $t = 43$ s).

results over time are presented in Fig. 10. The "x" symbol marked the position of UAS as reported by the sensors, the light blue ellipse is the projected distribution of UAS position in 20 seconds, and the aircraft alert zones shown is based on the projected aircraft position 20 seconds from the time of sensor input. At 20 seconds from the start of simulation (Fig. 10(a)), the UAS is tracked to be at (1480, -2000). The path prediction simulation forecast that an incursion into the aircraft TA area would occur in the next 20 seconds. At 43 seconds from the start of simulation (Fig. 10(b), the UAS is at (882, -2000), which falls within the TA zone of the aircraft at the time of sensor report,which was shown in lighter color. The collision simulation showed that the UAS could intrude into the CA zone of the aircraft in the next 20 seconds.

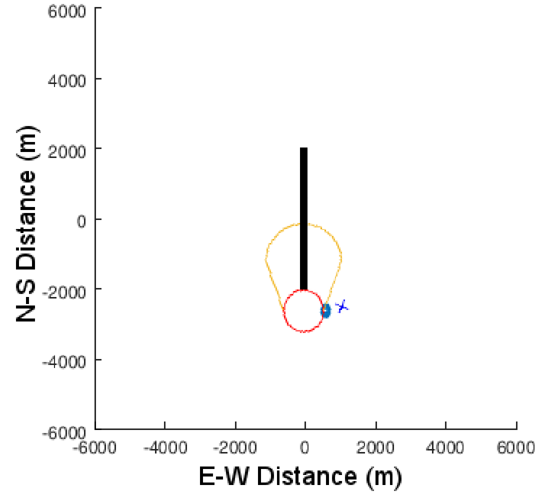


(a) CPA Method

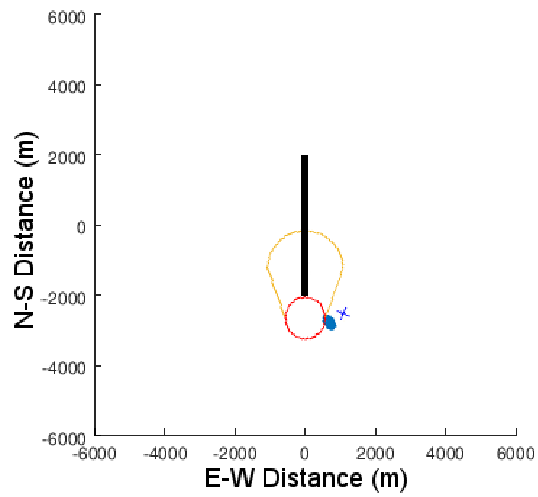


(b) Direction Retention Method

Fig. 11. The difference in collision assessment approach led to difference in collision prediction at $t = 21$ s, as (a) prediction using CPA method triggered TA alert, while (b) prediction that retained travel direction from sensor data did not.



(a) CPA Method



(b) Direction Retention Method

Fig. 12. At $t = 40$ s, neither (a) prediction using the CPA method, nor (b) prediction with last known direction of travel, forecast a triggering of collision warning in the next 20 seconds.

On the other hand, while the starting point of Track 2 is the same as Track 1, the warning for project incursion into TA zone was not predicted until 21 seconds after the start of the simulation, and only if the prediction was made using worst-case intention (using closest path of approach) (Fig. 11). A small shift in the predicted UAS positions towards the direction of travel in this case from the initial speed and direction of the UAS based on sensor data. Further along the track, the predicted TA zone incursion risk would slowly drops off until $< 50\%$ of the sample falls within the TA zone. By 40 seconds after the start of the simulation, simulations using both prediction method showed that the UAS would pass behind the airplane without posing a hazard (Fig. 12).

Note that no collision between the UAS and the landing aircraft occurred in the end, regardless of the collision prediction results. The results also showed that the inclusion of TA zone for collision risk assessment is redundant in this case, as its function overlaps with the 20 seconds UAS position forecast.

V. Conclusion

The investigation with the two tracks demonstrated that the availability of tracking data has the potential to reduce the rate of false collision warning while maintaining flight safety for the aircraft operating in the airspace. The simulations were limited to the first aircraft to enter the controlled airspace after the initial report of UAS sighting, as all subsequent flight would have to be suspended until the UAS is no longer a safety hazard, either as a collision risk or foreign object ingestion risk.

The static alert zones, while useful in preventing collision under worst-case scenario, does not account for the relative distance between the aircraft and the UAS. The boundary of this alert zone would also need to be adjusted for different UAS and aircraft type as well as different ambient conditions, such as crosswind. The pairwise alert zones faces limitations, but have a lower chance of false alert due to the smaller area covered by the alert zones. The simulations also showed high rate of change in the predicted collision risk near the boundary of the alert zones. For UAS with initial position near the alert zone boundary, a small deviation from the worst-case speed and trajectory would alter the result in collision prediction.

The incorporation of sensor data into the simulation using the two test tracks suggested that it could greatly reduce the false positive rate. Further study would be required to evaluate the two prediction approaches. The shortened forecasting-period requirement also reduces the deviation in the distribution of the projected UAS positions. While the two tracks investigated in this paper provided valuable insight into how the inclusion of sensor data would help in reducing false positive warning, the results are insufficient to obtain the statistics regarding difference in false warning rate from different methods. Further studies involve modifying the existing simulation code to accept randomized UAS track, based on known UAS performance, to obtain more data on detection rate.

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