A Drone Encounter Model for Detect and Avoid Evaluation in U-space

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***Abstract*—This paper introduces a Drone Encounter Generation (DEG) model designed to generate conflict trajectories between two or more drone unmanned vehicles. Conflict encounters are a key element in developing Detect and Avoid (DAA) systems, one of the cornerstones that should enable the safe extension of U-space into BVLOS operations. At the moment, no well-defined strategy exists in the literature to generate encounters between drones. Contrarily, in manned aviation, there exists a well-established tradition of generating large encounter sets based on realistic statistical information. DEG intends to fill this gap by enabling the modelling of the desired encounters, capturing the peculiarities of drone operations in U-space, and the different mission profiles that may exist. This work describes the initial efforts in defining the encounter modelling strategy and the algorithms employed to generate the necessary trajectories. For example, a potential DAA protection volume is analyzed as a potential use case demonstrating how the drone operational factor is captured correctly. The final objective of this work is to facilitate openly available encounter sets that could be employed by the research community to perform fair comparisons between DAA system proposals.**

***Keywords*—Encounter modelling, Drones, U-space, DAA systems.**

I. INTRODUCTION

Unmanned Aircraft System (UAS) operations are expected to grow significantly in semi-urban and urban areas. Current surveillance-oriented missions and future urban mobility operations will expand in duration and complexity due to the regulatory framework's consolidation. The upcoming traffic management systems for UAS (U-space system in Europe [1]) should provide the adequate basis to enable Beyond Visual Line of Sight (BVLOS) UAS operations.

The development of Remain Well Clear (RWC) and Collision Avoidance (CA) systems, commonly known as Detect and Avoid (DAA), is one of the cornerstones that should enable the UAS flight envelope extension. The DAA system definition and algorithms developed for large RPAS are already underway in the US and Europe based on DO-365B [2] and ED-258 MOPS [3] as well as many large-scale research projects. However, extensive research work is still necessary to adapt such concepts to the specifics of smaller UAS (usually called drones). Drones exhibit operational characteristics and flight dynamics that intrinsically differ from large RPAS; thus, a consistent conflict encounter analysis will require new mechanisms to generate the required test trajectories.

The literature available associated with the design of collision avoidance and trajectory deconfliction systems is enormous (see [4] as a reference). The literature associated with the design of DAA systems for drones is even more extensive (a limited review can be found here [5]). Many algorithms and techniques are proposed, including defining simple and complex protection volumes and proposing guidance functions to avoid conflicts. However, in the drone domain, there is no available research on the design of a comprehensive encounter set to be employed for testing and comparing the proposed DAA volumes and functions.

Defining an openly available set of realistic encounters should be the basis for determining critical parameters and safety levels associated with potential proposals of DAA functions in U-space [6], [7]. The same encounter sets could be employed to analyse separation, remain well-clear and collision avoidance system proposals. A common base of encounters offers the opportunity for a fair comparison between methodologies.

This paper describes a Drone Encounter Generation model (DEG) designed to generate conflict trajectories between two or more UAS. The objective is to provide a realistic set of drone-versus-drone encounters that exhaustively take into account all relevant conflict geometries. DEG is designed to generate operations in U-space, in which the flight plan (U-plan in U-space terminology) is the trajectory contract that the drone will execute. DEG inherits from existing encounter generation systems previously employed in Air Traffic Management (ATM) but introduces a novel generation strategy that considers all the peculiarities associated with drone flight-plan-based operations.

Trajectories are generated based on the assumption that BVLOS drones mostly fly structured flight plans executed by the onboard autopilot, with human manual supervision rather than manual control. Consequently, DEG generates encounter trajectory fragments given the probability that certain high-level flight actions would be performed. The detailed generation of each of the trajectories depends on the actual vehicle performance and is subject to the limitations of the sampled vehicle type.

Given the proposed encounter model and trajectory generation strategy, a collection of probability distributions describing the various aspects of UAS operations will be employed to generate an extensive set of encounters. Several encounter sets have already been computed under the proposed methodology, defined by different statistical parameters and variable distributions, including the vertical and horizontal miss-distance, encounter angle, speeds, altitudes, mission characteristics, etc.

The remainder of this paper will be structured as follows. Section II will review how encounter sets are generated in the ATM context and introduce other trajectory generation mechanisms found in the literature. Section III will outline the architecture of the DEG model and the main stochastical elements employed for generating drone trajectories and encounters. Section IV will detail the trajectory generation process, emphasising critical aspects associated with the specificities of drone operations, especially on the introduction of hover operations and accelerated behaviour. The section will detail, through an example, the encounter generation process. As the final goal of the encounter generation of the analysis of DAA functions, Section V will select some relevant encounters and apply a variant of the DO-365B remain well clear function, with parameters adapted to the drone conditions. Finally, Section VI will conclude the paper and introduce several future research aspects that should be addressed to determine the best DAA solution in the U-space context.

II. PREVIOUS RESEARCH

Over the years, various risk assessments have been performed to design and parameterise an Airborne Collision Avoidance System (ACAS) for manned aviation [8]. The availability of a large number of statistically significant conflict encounters has been paramount. Similar studies are currently being performed to determine the acceptability of future ACAS-X systems [9]. Given that the current level of safety greatly protects aviation from collision conflicts, the generation of realistic simulated trajectories has been the selected alternative to move forward.

The key objective of the DAA function is to support avoiding the violation of the well-clear and collision volumes of other vehicles. This support should be achieved by providing both alerting and guidance functionalities [10], [11]. The alerting functionality aims to determine whether an intruder poses enough risk to warrant an alert and, in this case, which alert priority is appropriate. Specifically, the DAA alerting function propagates the ownship and intruders measured state in order to evaluate the issuing of the following alerts (see Figure 1): Advisory alerts, indicating when a change in current course or altitude by the ownship may immediately trigger a Caution or Collision alert; Caution alerts, indicating a predicted or current violation of the well-clear volume, and Warning alerts, indicating that a remain or regain well-clear manoeuvre should be immediately executed.

The Lincoln Labs Collision Encounter Model (LLCEM) developed by MIT [8], [12] is one of the most accepted modelling systems. LLCEM, which was used to perform critical TCAS-II safety studies [13], has recently been extended to support the integration of RPAS in the NAS and the analysis of the Remain Well Clear functionality [14]. LLCEM is based on the use of Bayesian Networks [15]. A Bayesian network is a probabilistic graphical model representing a set of variables exhibiting a random behaviour. A directed acyclic graph is used to capture conditional dependencies between variables. Bayesian networks represent the relationship between the key variables defining pairwise encounters, e.g., relative altitude, speed, angles, etc.

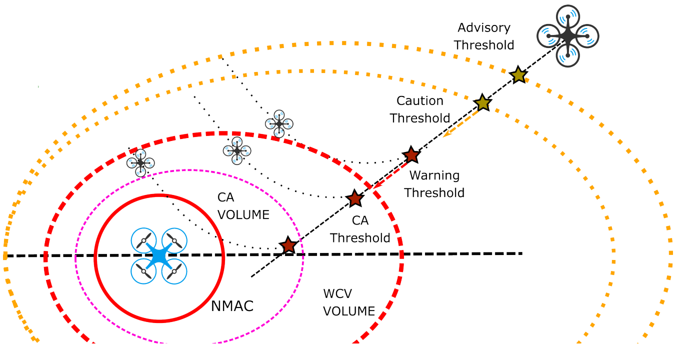

Figure 1. General structure of a potential drone to drone DAA encounter.

Recently, the Eurocontrol *Collision Avoidance Fast-time Evaluator* (CAFÉ) *Revised Encounter Model for Europe* (CRÈME) has been introduced as a new generation ACAS analysis tool [16]. CAFÉ is also based on Bayesian Network modelling as the LLCEM toolset but exploits improvements in software design and network modelling to satisfy the needs and specificities of the European airspace. In addition, CAFÉ introduces new capabilities like aircraft classes, limited modelling of wind fields, and the possibility of generating multi-aircraft encounters. Those elements are intended to improve the realism of the generated trajectories when addressing the RPAS peculiarities.

CAFÉ is based on over 12 million European radar data from 2015-18 flight hours from six Air Navigation Service Providers (ANSP) controlling several European countries (Belgium, Czech Republic, France, Germany, Luxembourg, Netherlands, Poland, Switzerland, and the UK). The CAFÉ implementation significantly modifies that model to simplify the generation process and make it more realistic.

Both the original LLCEM and CAFÉ focus on generating an aircraft trajectory independent of its flight plan. The aircraft location, speed vector, and acceleration change throughout the trajectory generation process. The reasoning behind that decision is that collision encounters may only last 50 to 120 seconds, and therefore the aircraft flight plan has no actual impact on the conflict evolution. Other models have also been developed to evaluate separation assurance based on the structuring of the encounter and the statistical generation of realistic parameters for each encounter [17], [18].

On the contrary, little effort has been put into the encounter modelling for small UAS. Rather than developing generalistic encounter models, we have identified that authors use several ad-hoc strategies, namely: (1) *Simple geometry*: pairwise encounters are generated by fixing a point of minimum approximation and generating sets of linear trajectories, changing the angle of the encounter, speeds, and descent/climb rates [19]–[21]. (2) *Cube-based geometry*: a cube-like fixed volume is defined, and vehicles located at one face of the cube travel to an opposite face [22]. Encounters are generated, and some of them are discarded if did not contain a relevant conflict. (3) *Operational Scenario*: in order to increase the realism of the generated encounters, operational scenarios are selected, like operations in a city, harbours, logistic areas, etc. (4) *Realistic Mission*: broader geographical areas are selected, and realistic drone missions are extensively reproduced [23], [24].

Such methodologies offer little statistical control over the parameters defining a conflict (distances, angles, involved speed, manoeuvrability level, etc.). Moreover, there is a considerable likelihood of generating trajectories that only occasionally lead to encounters, thus wasting computational effort. For this reason, the authors believe that the safety analysis for drone DAA systems needs to employ the same techniques that have been well established in the ATM domain but consider the peculiarities associated with drone operations.

III. Encounter Generation Strategy

The encounter variables in the DEG model estimate the actual conditions of future U-Space environments and are stochastically sampled from several probabilistic distribution tables. The encounter generation strategy assumes that drones operate a U-plan, so their trajectories are structured rather than just performing a free flight. This strategy is widely different from other approaches, in which the trajectories are generated by modelling the flight dynamics rather than the U-plan structure.

DEG generates random pairwise trajectories between non-cooperative medium and small-size drones in the final stages before a collision. The way trajectories are formed is strongly influenced by the type of operation performed. In DEG, various types of operations and vehicle performance characteristics could be modelled by trimming some of the encounter parameters discussed later in the section.

A. Generation of U-plan Segments

The creation of an encounter is based on generating independent trajectories, one for the drone considered Ownship and a second for the Intruder. The Intruder trajectory will then be transposed and rotated to adjust it to the desired Closest Point of Approach (CPA) parameters.

A four-phase process generates the trajectories. First, segments of the U-plan are stochastically generated by a sampling procedure described in this section. Each U-plan segment is, in turn, transformed into a sequence of waypoints to be flown. Then, a simulation process generates a point sequence corresponding to how a drone flies the generated U-plan fragment. Finally, trajectories are combined and adjusted. The overall process is detailed as follows:

1) DEG defines the desired Ownship and Intruder trajectories by generating their underlying U-plan flight segments. Segment generation starts from an initial reference point selected as CPA, in which a Near Mid-air Collision (NMAC) may occur. Then, further segments are generated forward and backward until the encounter duration conditions are met (two or three minutes before the CPA and almost a minute after the CPA).
   Segments specify the initial and target altitudes, speeds, and flight duration for each interval based on high-level horizontal actions, vertical actions and speed-related actions (to be detailed later).
2) Based on the available segments, DEG calculates the actual 4D waypoints that will constitute the intended flown trajectory by linearly projecting the pre-calculated segment parameters.
3) Once 4D waypoints are calculated, DEG employs a drone kinematics and dynamics package that, through iterative analysis, reproduces the drone model's flight through each 4D waypoint. During the simulation, the drone state derivatives (position, speed, and course) are updated from waypoint to waypoint by controlling the drone's attitude and speed vector.
4) Finally, once both the Ownship and intruder's trajectories have been computed, DEG translates and rotates the Intruder trajectory to match the Ownship trajectory based on the required CPA encounter parameters.

B. Segment Parameters

Segments are defined by several parameters associated with the drone behaviour: (1) the horizontal mode, (2) the vertical mode, and (3) the acceleration mode, whose combination will be employed to compute the actual flight trajectory according to the drone's performance.

The segment horizontal mode could be of three types:

- Straight segment: the drone keeps its course on the horizontal plane.
- Turn segment: the drone performs a turn, right or left, measured by a course variation.
- Hover segment: the drone stops mid-air with no horizontal velocity (although vertical velocity may exist).

The segment vertical mode could be of three types:

- Level-flight segment: altitude is maintained regardless of the horizontal mode.
- Climb segment: altitude increases by a certain value.
- Descent segment: altitude decreases by a certain value.

Finally, the segment acceleration mode type:

- Non-accelerated segment: in which the horizontal speed is maintained.
- Accelerating segment: the horizontal speed is increased.
- Decelerating segment: the horizontal speed is decreased.

Certain conditions must be met when generating a sequence of segments, like altitudes, velocities, and course, which should coincide at the end of one segment and the start of the next. However, the introduction of hovering segments requires taking into account additional restrictions. Segments preceding a hover segment should already be in hover mode or be of the deceleration type, leading to zero horizontal speed so that the hover may start (note that any vertical mode is possible).

Similarly, the transition from a hover segment may proceed to either another hover segment or an accelerated segment to attain the desired horizontal speed.

Finally, segment parameters should be bounded to realistic physical and operational values. Stochastically sampling specific values like speed and altitude variations may lead to negative speeds or speeds beyond the capabilities of drones. Similarly, altitudes may need to be managed carefully, avoiding negative altitudes or altitudes above those authorized for drone operation.

C. Segment Parameter Estimation

The encounter variables in the DEG model estimate the real drone operational conditions that we may find in future U-Space environments and are stored in several probabilistic distribution tables. Realistic drone trajectories would then be generated by sampling these probabilistic distribution tables.

DEG requires two key probabilistic distribution tables to proceed with the trajectory generation process: the *Initial Distribution* table and an *Aircraft Class* table for each vehicle type considered in the analysis. Each specific distribution is created as a parameterized instance of a continuous random variable. The Initial Distribution table contains the CPA encounter parameters described in Table I.

TABLE I. INITIAL DISTRIBUTION TABLE CONTAINING THE KEY VARIABLES AT CPA.

Distribution	Description
VMD	Vertical miss distance (m)
HMD	Horizontal miss distance (m)
App Angle	Approach angle (deg)
Altitude	Altitude for ownship (m)
Speed	Relative speed (m/s)
Type	Ownship/Intruder drone type

The *Aircraft Class* table contains three types of probability parameters about operational dynamics that will employed to generate the U-plan segments: (1) basic dynamic parameters like speed and variation rates; (2) commands to be executed in the segment; and (3) variations and time duration. A resume of the most relevant parameters is found in Table II, where Type P indicates a *Performance* distribution, C a *Navigation Command* distribution and V an *Operational Variation* distribution.

TABLE II. AICRAFT CLASS VARIABLES FOR ALL U-PLAN SEGMENTS.

Name	Type	Description
Speed	P	flying at a speed (m/s)
Climb Rate	P	climbing at a rate (m/s)
Descent Rate	P	descending at a rate (m/s)
Turn Rate	P	turning at a rate (deg/s)
Acceleration	P	horizontal plane acceleration (m/s^2)
Horizontal	C	prob. of Straight, Turn or Hover
Vertical	C	prob. of Level, Climb or Descent
Speed	C	prob. of Non-Accel., Accel. or Decel.
Speed	V	changing speed by amount (m/s)
Altitude	V	changing altitude by amount (m)
Course	V	changing course by amount (deg)
Seg. Duration	V	flying for a certain time (sec)
Hover. Duration	V	hovering for a certain time (sec)

Determining the Aircraft Types to be considered and which performance and operation factors are employed by each one of those classes remains open to investigation. Collecting realistic drone operation patterns could be the way to distil the required information. Currently, the probabilistic distribution tables do not fully reflect reality because there is a lack of actual operational data. Consequently, the tables have been populated with expert information derived from experiences with simulations and validations in real-world environments.

IV. DETAILED TRAJECTORY GENERATION

A. U-plan Segment Generation

The generation of the U-plan segments starts by sampling the CPA encounter conditions from the corresponding probabilistic distribution tables. These variables characterize the high-level parameters of the encounter and the relative position between the Ownship and Intruder, defined by VMD, HMD, Relative Speed, Relative Approach angle, and Ownship and Intruder vehicle class.

Ownship altitude at CPA is sampled from the corresponding distribution table, and the corresponding Intruder altitude is derived accordingly. Note that if the VMD distance distribution is entirely composed of non-negative values, then intruders are always located above or level to Ownship at CPA.

A characteristic of the current implementation is that the relative speed between both vehicles at CPA is sampled. Then, separate speeds at CPA are sampled for Ownship and adjusted accordingly for the Intruder. Note that speeds may need to be capped according to the performance limitations of the selected vehicle class.

NMAC segment: Once CPA parameters have been sampled, the base NMAC segment parameters will be determined. We refer to the NMAC segments as the portion of the U-plan that contains the CPA for both Ownship and Intruder. The whole U-plan will be generated from this initial CPA segment by concatenating additional segments backwards and then forward until the desired duration is attained.

The basic NMAC segment parameters must be compatible with the CPA point's location within the segment. CPA is determined by sampling a unitary form value (CPAFactor) ranging from 0 to 1, specifying the CPA location as a fraction of the total NMAC segment. Once the CPAFactor has been determined, the NMAC segment for a U-plan is computed by sampling:

1) `The vertical mode (Level-flight, Climb, or Descent).`
    - `Sample altitude variation (if it is not a Level-flight segment).`
2) `The horizontal mode (Straight, Turn or Hover).`
    - `If mode is Turn, sample course variations and turn rate. Segment duration determined by time to achieve course variation according to turn rate.`
    - `If mode is Hover, sample hover duration.`
3) `The acceleration mode (Non-accelerated, Accelerating or Decelerating).`
    - `Sample speed variation (if it is not a Hover or Non-accelerated segment).`

4) Speed at the start/end of the segment, determined as:
    - Adjust sampled speed at CPA, speed variation and percentage provided by the CPAFactor.
    - Trim speeds within performance values, i.e. greater than zero and smaller than maximum speed.
    - Readjust CPAFactor to maintain general coherence.
5) Altitude at the start/end of the segment, determined as:
    - Adjust sampled altitude at CPA, altitude variation and the percentage provided by the CPAFactor.
    - Trim altitude within allowed values, i.e. greater than zero and smaller than maximum allowed altitude.
    - Readjust CPAFactor to maintain general coherence.

Note that additional altitude coherence rules may be necessary, e.g. climbing while at maximum altitude, which are not described due to the lack of space.

Forward Segment Generation: The forward and backward segments are generated following a similar logic but taking into consideration the initial and final parameters of the adjacent segments. The following procedure determines the forward segment parameters by sampling:

1) The Forward horizontal mode (Straight, Turn or Hover).
2) If horizontal mode is not a Hover:
    - If mode is Turn, sample course variation and turn rate. Segment duration determined by time to achieve course variation according to turn rate.
    - If mode is not Turn, sample segment duration.
    - If previous speed is 0 and segment is not Hover, the acceleration mode should be Accelerate.
    - Sample acceleration mode (Non-accelerated, Accelerating or Decelerating).
    - If it is not a non-accelerated segment, sample speed variation. Speed at end of the segment is determined by adding the speed variation and limiting it to min/max speeds according to performance.
3) The Acceleration mode (Non-accelerated, Accelerating or Decelerating) unless already determined.
    - Sample speed variation (if it is not a Hover or Non-accelerated segment).
4) The Vertical mode (Level-flight, Climb, or Descent).
5) If vertical mode is not Level-Flight:
    - Sample the altitude variation.
    - Apply altitude variation according to vertical mode.
    - Apply min/max altitude limits.
    - If the horizontal mode is a Hover, duration according to the vertical speed
6) If vertical mode is Level-Flight and horizontal mode is Hover:
    - Sample the hold duration time

To illustrate the DEG process, we selected an encounter that includes some differential aspects compared to other trajectory generation systems. The encounter parameters at CPA are described in Table III, where O/I indicate Ownship/Intruder, ALT/SPD/APA/TYPE altitude/speed/approach angle/type, and SID/SDD a Small Inspection Drone and Small Delivery Drone, respectively.

TABLE III. CPA PARAMETERS FOR THE EXAMPLE ENCOUNTER.

VMD	1.63	HMD	40.09	APA	20.23
O ALT	73.37	O SPD	4.21	O TYPE	SID
I ALT	75.01	I SPD	4.5	I TYPE	SDD

Ownship and Intruder segments and generated trajectories are shown in Figure 2 and Figure 3, with black lines representing the sampled segments and the yellow points representing the flown trajectories. The diagrams depict the horizontal path, altitude/time diagram and speed/time diagram.

The NMAC segment for Ownship starts decelerating (Figure 2) down to a hover at around $72\,m$ of altitude. Sampling forward, the drone will keep holding for a long time while climbing above $76\,m$. Then, descend and initiate a slow forward movement until around $74\,m$. After the initial hold, the drone will turn to course 67.15^o. Sampling backwards is made easier by a short forward segment, followed by a turn coming from course 337.45^o, and then two more forward segments. Altitude will be maintained around $72\,m$ meters, continuously decelerating until the drone holds at CPA.

The NMAC segment for Intruder starts at a forward constant velocity (Figure 3), climbing from approximately $70\,m$ to $75\,m$. Sampling forward, a series of turns are performed, maintaining the altitude and slightly decelerating. Sampling segments backwards, another series of short segments and turns are sampled, maintaining $70\,m$ and decelerating.

B. Waypoint and Trajectory Generation

Waypoints would be computed based on the segment duration and speed variation depending on whether the drone remains at a constant speed, accelerates or decelerates. If the previous segment has zero horizontal speed, then the next segment's speed mode should be Accelerating. The segment duration was sampled from the distribution if the speed mode is constant or the horizontal mode is Hover. Speed variations and target waypoint speeds are adjusted for each segment according to vehicle performance and speed modes. If the target speed is greater than 0 m/s and the next segment's horizontal mode is Hover, then we should calculate the time and distance required to decelerate the drone to the desired hover (currently using a $g/2$ deceleration factor).

Once all speeds and durations are determined, each waypoint's latitude/longitude and altitude can be adequately determined and used to generate the actual flight trajectory. The last factor considered is the addition of an initial stub segment, which allows the drone trajectory generation to start from a zero-speed position and then accelerate to the desired operational speed assigned to the first segment. This stub segment is later removed to obtain the actual trajectory, as it is not part of the sampled sequence of segments.

Once the desired waypoint sequence is available, a simulation generates a realistic drone flight trajectory. For this

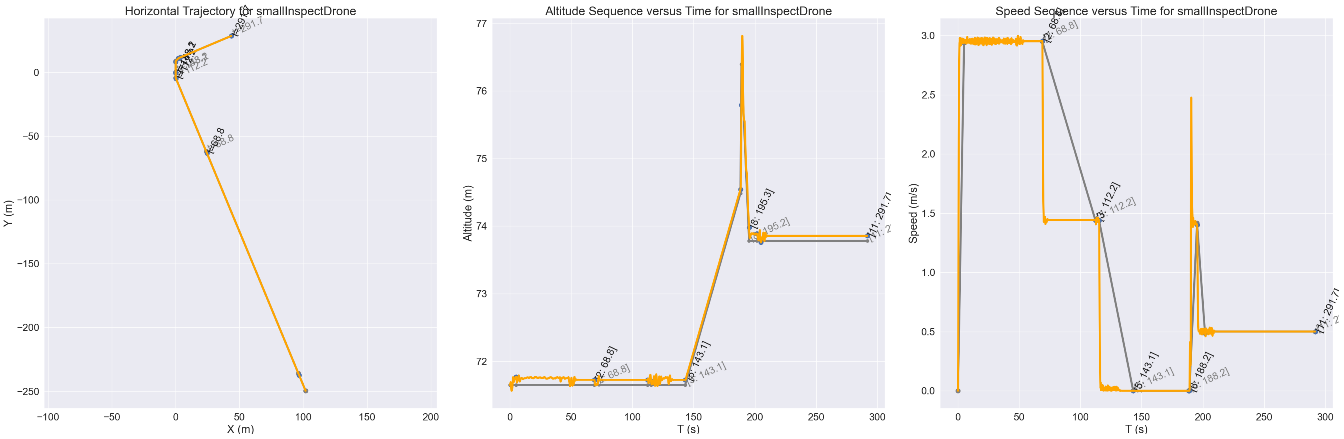

Figure 2. Ownship waypoint and trajectory sequence with (left) horizontal path, (center) altitude/time diagram and (right) speed/time diagram.

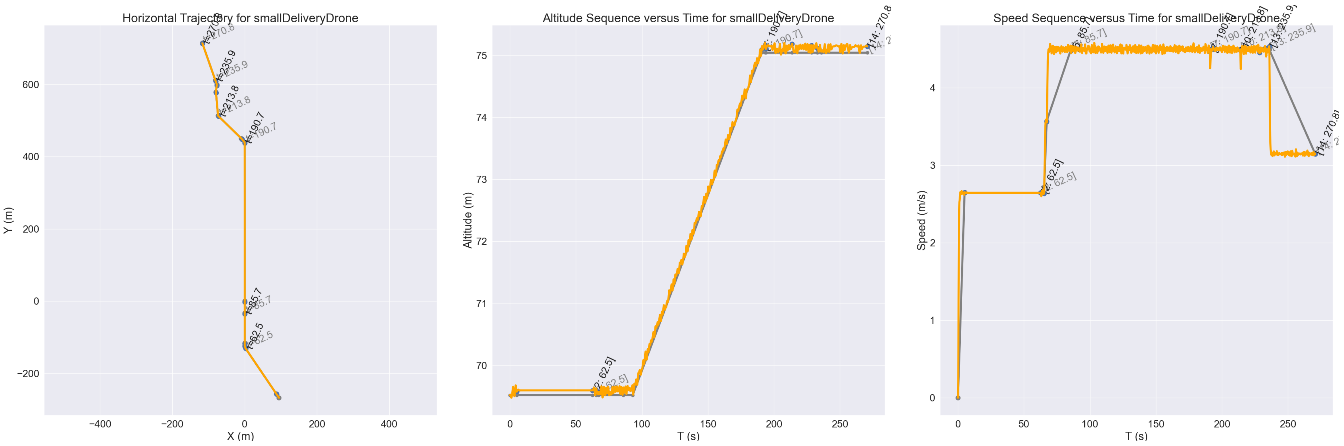

Figure 3. Intruder waypoint and trajectory sequence with (left) horizontal path, (center) altitude/time diagram and (right) speed/time diagram.

purpose, we employ the PyDy (Pyhton Dynamics) package, designed to research multibody dynamics [25]. This library provides a robust framework for simulating the behaviour of mechanical systems, which allows the generation of the equations of motion of complex systems. To properly govern the drone's behaviour, three controllers have been required to be implemented: one for regulating XY positions, another for regulating XY velocities and Z positions, and a third for regulating XYZ velocities. These controllers are based on the PX4 multicopter control algorithm. Currently, our implementation is limited to a quadcopter vehicle modelled by a six-degree-of-freedom system expressing the drone's kinematics. This limitation only applies to the trajectory generation and not the rest of the methodology, which can support multiple vehicle types (multicopters, aircraft, helicopters, or hybrids) by adjusting the performance and operational variable distributions. Moreover, note that the generated trajectories include some level of discontinuity and oscillations due to the combination of the vehicle model and the adjustment of the PX4 control loops.

Employing such a complex trajectory generation strategy is a limitation to expanding the analysis to a broader range of vehicles. At the moment, alternative strategies for drone trajectory generation are being investigated. These strategies should be flexible enough to incorporate new drone types and less computationally intensive to facilitate the generation of large sets of encounters. These alternative trajectory generation strategies should not impact the proposed encounter methodology, independent of actual drone performance details. Once individual trajectories have been generated for Ownship and Intruder from whatever methodology, they still need to be adjusted to the desired CPA parameters (see Figure 4). This adjustment should be performed from the timing and the geometrical point of view:

- The trajectories' start and end must be trimmed to a common duration.
- The Intruder trajectory is translated and rotated so that the designated CPA points coincide with the desired HMD/VMD and Approach angle parameters.

V. RWC ENCOUNTER ANALYSIS

The definition and implementation of systems that help prevent mid-air collisions between drones and between drones and manned aviation in U-space is still the subject of investigation. It is generally understood that some Detect and Avoid (DAA) capabilities need to be developed, although consensus still needs to be reached on which protection volumes should be employed and which systems should implement those functions. The sole purpose of the DEG platform is to generate the necessary conflict encounters, which could help carry out the necessary comparative safety analysis, leading to the selection of the most appropriate protection volumes.

DAA systems provide surveillance, alerts, and guidance to help drones remain well-clear from other vehicles. In the RPAS context, different studies have been carried out to define algorithms and protection volumes that serve as a standard of the Minimum Operational Performance Standards (MOPS) for DAA systems. Depending on the operational and regulatory environment, the DAA systems should provide means for Remain Well Clear (RWC), Collision Avoidance (CA), or both.

The ICAO's Manual on RPAS [26] defines the concept "Remain Well Clear" as "the ability to detect, analyse and manoeuvre to avoid a potential conflict by applying adjustments to the current flight path in order to prevent the conflict from developing into a collision hazard". When RWC functions cannot mitigate the conflict and the aircraft enters the protection volume, the CA functions issue alerts and guidance manoeuvres to prevent a Near Mid Air Collision (NMAC).

The Well Clear Volume (WCV) refers to an airspace volume around an aircraft, producing a well-clear violation if an intruder enters. Similarly, the CA volume is a smaller volume around the aircraft within which, if an aircraft enters, it is considered a collision threat (recall Figure 1).

Although no consensus exists in the drone domain, in aviation, the collision avoidance protection volumes are generally defined by a disk-shaped volume, horizontally defined by a combination of time-modifiers (TAUMOD), distance-modifiers (DMOD), and vertical (ZTHR) limits. The horizontal limit is made larger in the direction of aircraft movement (speed vector) by applying the TAUMOD modifier to compensate for higher closure rates. Based on these volumes, the following alerts are designed:

- Preventive Alert: Also classified as an Advisory Alert, indicates that a change in current heading or altitude by the Ownship may immediately trigger a Caution alert. The drone response to an advisory level alert should monitor the designated traffic by assessing the overall situation of the encounter and be aware of the risk of inducing a loss of well-clear situation due to possible future manoeuvres or mission constraints.
- Caution Alert: Also classified as a Corrective Alert, indicates a predicted (within a given look-ahead time) or current loss of well-clear situation. This alert necessitates immediate awareness of the drone pilot and subsequent actions to maintain or regain the well-clear condition.
- Warning Alert: Imply immediate action to prevent violating the CA volume. (Note that it may be argued that a Warning alert is almost equivalent to a CA alert.)

A demonstrative analysis will be performed on the example encounter based on a proposed set of RWC parameters as shown in Table IV. As it can be observed, Warning, Caution and Preventive volumes are defined. The Warning and Caution volumes share the same DMOD/TMOD and H parameters but with an increased Time Threshold. The Preventive function employs a slightly enlarged protection volume and Time Threshold. The table also includes an NMAC definition.

TABLE IV. RWC PARAMETERS FOR THE EXAMPLE ENCOUNTER.

Function	Threshold	TMOD	DMOD	H
NMAC			15	5
Warning	20	35	60	40
Caution	45	35	60	40
Preventive	55	35	60	60

Figure 4 describes the results of an open loop encounter analysis in which the vehicle does not manoeuvre to avoid the collision conflict. Open loop analysis is generally employed to test the level of protection offered by the DAA volumes and functions, while close loop encounters are employed to test the performance of the avoidance systems.

The figure represents the encounter with its horizontal path, altitude/time diagram and horizontal/vertical distance diagram. The activation of the Preventive function is indicated in Green, while the Caution and Warning functions are indicated in Yellow and Orange, respectively. If the WC volume is violated, it is indicated in Red, while if the NMAC volume is violated, the same Red colour is employed (but with a thicker line). As it can be appreciated, the encounter trajectories converge, and the various well-clear functions activate progressively up until the trajectories diverge and the conflict clears up. The diagrams also show that a wide time margin is available from the first activation of the Caution function until the WC volume is violated. Hence, the DAA function seems to provide the desired protection.

Figure 5 depicts another encounter belonging to the same encounter set, in which neither the preventive, caution or warning function protects from the incoming encounter. One of the drones initiates a holding for around a minute while a second drone crosses in an almost perpendicular trajectory. The first drone exits the holding unexpectedly. The sudden and aggressive acceleration is excessive for the protection the employed WC volumes offer. The sudden increase in relative speed increases the TMOD factor of the WC volume, leading to an immediate violation of that volume (the CPA parameters being VMD: $36.3\,m$ / HMD: $16.7\,m$).

These examples demonstrate that a deeper analysis is required in selecting DAA protection volumes and functions that provide a reasonable safety level for drone operations. Some of the proposals in the existing literature seem to have ignored accelerated encounters, which clearly justifies the need for employing representative encounter sets.

VI. CONCLUSIONS AND FUTURE WORK

We introduced DEG, a model designed to generate realistic drone-to-drone encounters. Extensive sets of realistic encounters should be employed to determine critical parameters associated with the DAA function in U-space and the overall safety level for each given alternative. The same encounter sets could be employed to analyse separation or remain well-clear

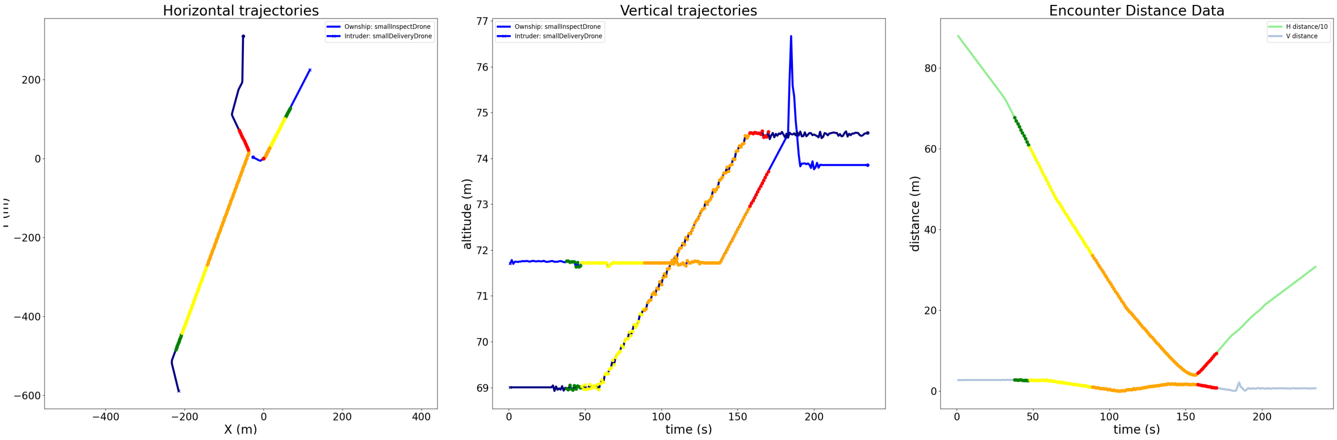

Figure 4. RWC encounter representation with (left) horizontal path, (center) altitude/time diagram and (right) horizontal/vertical distance diagram.

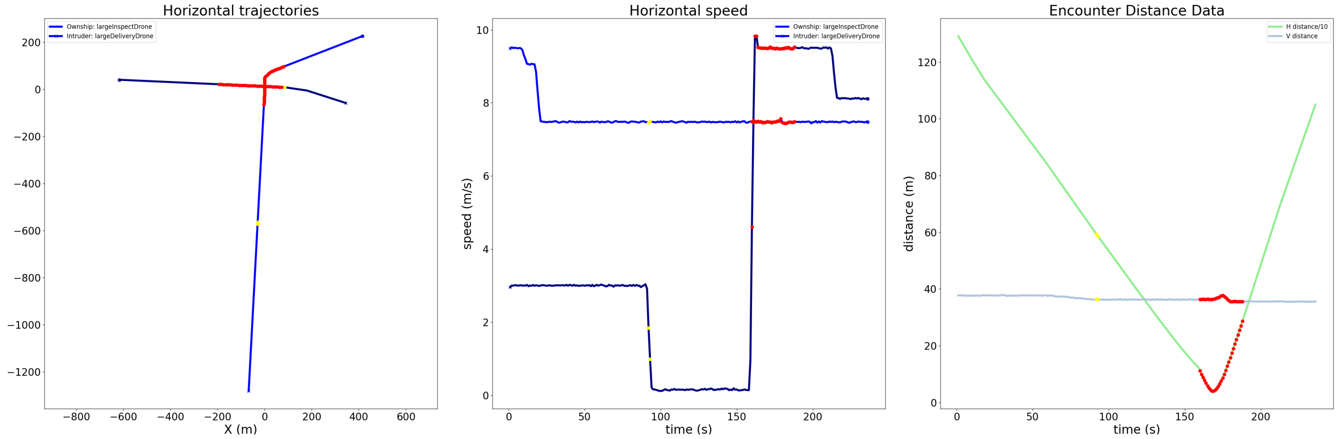

Figure 5. RWC encounter representation with (left) horizontal path, (center) speed/time diagram and (right) horizontal/vertical distance diagram.

and collision avoidance systems. DEG is designed to model structured operations in U-space, in which the U-plan has the utmost relevance compared to non-structured or free flight operations. DEG learns from existing encounter generation systems previously employed in ATM (like LLECM and CAFE) and proposes a novel strategy in which the trajectories are generated considering all the peculiarities associated with VTOL operations. A small analysis of a potential RWC function has been employed to demonstrate the complexities of such evaluation and the usefulness of the DEG-generated trajectories in raising key safety aspects.

The current proposal should be considered a starting point, as a wide range of research areas are open to improving drone encounter sets' generation. The most immediate, which limits the generation capacity, is the development of drone performance models and accurate and efficient trajectory generators based on that performance model.

Access to drone operational data would improve the specification of the Initial and Transition Tables in DEG. The generation of drone encounters not only depends on the accurate modelling of their performance but also the modelling of their operational behaviour. This is achievable by collecting historical data, an effort that, in fact, is already occurring, led by Eurocontrol within the U-space Airspace Risk Assessment initiative [27].

Correlations could be discovered based on operational observation, which, if incorporated into the model, would improve the realism of the generated encounters. Adding variable correlations, e.g., certain conflict speeds tend to occur at certain altitudes, could be easily integrated into DEG by increasing the dimensions of some of the Initial and Transition Tables and adding the selected stochastic dependencies in the sampling process.

Finally, drone-to-drone encounters are expected in U-space, but drone/manned aircraft encounters may also occur once full integration is achieved. Adding traditional manned aircraft modelling in DEG is feasible, as the mechanisms are well-known from the previous LLCEM/CAFE experience. U-space services will capture drone trajectories, but the complex part of the process would be extracting the operational characteristics of small aircraft when operating at a low level. Radar or ADS-B coverage at those altitudes is scarce; therefore, it is hard to capture flight traces, which may lead to determining the necessary probability information.

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