A method for determining the safe separation to an unknown-model uncooperative UAV in U-space

Ivan Panov*[*], Jes Jepsen**, Mirko Presser* and Kjeld Jensen**
* Department of Business Development and Technology, Aarhus University, Herning, Denmark 7400
** SDU Drone Center, University of Southern Denmark, Odense, Denmark 5230

ABSTRACT

Unmanned aerial vehicles (UAVs), often referred to as drones, usher in a new era of aviation by delivering new services at very low-level airspace. Many technical and organisational issues must be addressed to ensure flight safety at the European level. This paper proposes a novel method for addressing the challenge of ensuring a safe minimum separation distance between a conventional drone (CD) and an uncooperative drone (UD) of an unknown model (UDUM). A CD follows regulations and maintains communication with other U-space traffic participants, while a UD conducts a non-conformance flight without permission from the U-space service provider (USSP), thereby posing a significant threat to flight safety.

Our safe separation method relies on a global UAV database analysis and assumes that a vision system or other passive sensing technology (a recognition system) can identify the type of UAV of an unknown model. Additionally, the method involves determining the minimum separation distance and safety radius of a UDUM using velocity vectors for both the CD and UDUM and performing geometric optimisation.

Our UDUM classification led to a significant improvement in measuring the minimum separation distance, resulting in an up to fivefold optimisation among different types of UAVs. We recommend the method for the future autonomous guidance system of CDs.

1 INTRODUCTION

U-space, the European implementation of an unmanned aircraft system traffic management (UTM) system, is expected to support UAV operations with very high levels of automation [1, 2, 3] including autonomous UAV guidance that relies on the planning of safe 4D trajectories encompassing three dimensions and time [4]. The autonomous system will rely on automated rule-based systems and, potentially, artificial intelligence to plan trajectories and continuously replan [4].

Collision avoidance is a fundamental principle of flight [5]. Through their literature review, J. K. Kuchar et al. made a significant contribution to the field by categorising the existing methods [6]. Some scientific articles have proposed various collision avoidance approaches for CDs [7], [8]. The performance and intentions of UDUM aircraft are unknown; therefore, classical methods such as probabilistic and deterministic approaches cannot be used, as they rely on this data. If U-space airspace is violated by a UDUM, it introduces an elevated risk of potential collision with surrounding aircraft. The fundamental question here is what "surrounding" means; in other words, what is the safe separation distance needed for each case.

In this paper, we discuss various UAV models and types. UAV models are characterized by a unique design or configuration, including specific features such as weight, size, and propulsion system. In contrast, UAV type refers to the physical configuration, operational characteristics, or usage of the UAV. We categorize UAVs into the following types: fixed-wing, rotary-wing, lighter-than-air, flapping-wing, and parafoil. For example, the DJI Phantom 4 is a model, and its type is rotary-wing.

M. Wisniewski et al. [9] proposed to use neural networks to identify a UAV model using its image. The safe separation distance of a known-model UD (UDKM) can be determined if the autonomous guidance system has information about the UDKM's position, aircraft performance and, ideally, its vector of velocity. However, if the UD's model is unknown, finding the minimum safe separation distance becomes significantly more complicated. To the best of our knowledge, there is no known effective solution for determining the minimum safe separation distance of UDUMs. If a UDUM is fast enough to collide with a CD before the flight terminates, and the autonomous guidance system of the CD does not adequately account for this situation, there is scope for flight safety improvements.

We argue that even if the recognition system is unable to identify the model of UD, at least it must be able to identify the UDUM's type based on its image and/or its current speed. Knowing the type of UDUM is essential for calculating the minimum safe separation distance between a CD and a UD. The simple alternative solution of having a standard safe separation distance for all types of UDUMs leads to inefficient

[*]Email address: ivan.panov@btech.au.dk

U-space airspace usage. This can be especially important for high-density unmanned air traffic.

To tackle the problem, we decided to approach the issue from a new angle. More specifically, we analysed the global database of UAVs [10], which contains information about the maximum speed in horizontal flight of almost 3,000 UAVs. One of our research objectives was to find the maximum speed of each type of UAV.

We start the paper by explaining the assumptions and the research method. After that, we discuss the results of the global database [10] analysis. Then we present a method for using drone-type classification to ensure safe minimum separation. Subsequently, we propose a geometric approach to determining an optimal margin for safe separation. To give an example of how it can be used, we solve a task involving a case scenario of a potential collision. We also discuss whether our method can be used for other cases. Finally, we present a conclusion in the last section.

2 Problem formulation and research method

We advance the hypothesis that if a UD's model is unknown, it is essential to know the maximum speed of its type, the minimum and maximum value of drag coefficient for the type, the aircraft dimensions to predict its cross-sectional area and the maximum and minimum mass range. Based on this information, we propose a method to suggest a safe separation distance between UDUMs and conventional U-space air traffic. The research question is how to find the minimum separation distance and safety radius of UDUMs to prevent collisions with CDs. A safety bubble will likely have a non-spherical form (Figure 8). However, in our simplified approach, the safety bubble is created by calculating the longest distance possible to fly in a predetermined value of time (Figure 8). The points obtained from the calculations are symmetric along the vertical axis, which allows us to discuss minimum separation distance and safety radius on the horizon at a certain altitude (Figure 9).

2.1 Assumptions

Based on the progress of machine learning techniques, we employ the assumption that an artificial intelligence system will be able to identify the type of any drone based on its image [9], [11].

We also make the decision to exclude the fastest highly advanced UAVs from the database, as it is highly unlikely that their model would be unknown. High-speed flight performance requires expensive technologies like jet or turbo engines [12]. Building a compound helicopter model involves very complicated [13] research and development processes, which sets a high bar for making this type of UAV. However, a simple quadcopter can be constructed in a garage or in a drone club by a layman [14]. In the latter case, the UAV's model can be unknown to the drone recognition system, and the CD's autonomous guidance system will not be able to predict a safe separation distance to the UDUM since its performance is unknown. One could argue that certain drones and rockets can fly at supersonic or even hypersonic speeds. However, once again, these technologies are not widely available, and safe separation from them should not be an operational issue for U-space airspace. Protection against such threats is related to defensive technologies and remains outside the scope of the current study.

We propose a solution for 4D (3D + time) space based on the global UAV database, where we categorise various types of UAVs and determine the maximum horizontal flight speed for each type. However, our database is limited in terms of aircraft model, type, and maximum speed, leading us to rely on assumptions concerning drag coefficient, cross-sectional area and mass of the UDUM. We acknowledge that further research is needed to find dependencies between the dimensions of a UAV and its maximum and minimum mass, cross-sectional area and drag coefficient. Based on the data on the UDUM's dimensions and type, the autonomous guidance system can calculate the safe separation distance using our method.

The limitations by type could help achieve collision-free flight in the vicinity of UDUMs operating at different altitudes. Aerodynamic drag, thrust, and mass significantly impact aircraft acceleration, deceleration, and maximum dive speed. While fixed-wing or rotary-wing UAVs may have lower drag coefficient values, some UAVs classified as airships have a large cross-sectional area, which leads to a higher value of the drag coefficient [15]. The greater the drag value, the more severe the limit of maximum diving speed due to the balance of aerodynamic forces [16].

Finally, we did not take into consideration the impact of weather conditions and other specific constraints [17] like restricted areas, sensor accuracy impact, etc. We also chose to disregard the air compression effect, as the increase in drag coefficient with rising speed does not have a detrimental impact on flight safety. Also, the drones we focus on rarely fly significantly faster than 100 m/s. The fastest UAV in our refined dataset has a maximum speed of 118 m/s, and at this velocity, the impact of the effect is relatively small. To fly significantly faster, the drones must dive with a large negative flight path angle γ, which they can only do within a short time interval.

2.2 Research method

In accordance with our assumptions, we refined the global UAV database by excluding the fastest highly advanced UAVs. Subsequently, we checked the maximum speed for each drone type. We developed a novel method, MATHryoshka, that uses data on maximum velocity, drag coefficient, cross-sectional area, mass, and current velocity of UDUM to calculate minimum separation distance and safety radius. To minimise the risk of collisions, we proposed an approach that involves measuring the safe separation distance.

3 GLOBAL UAV DATABASE ANALYSIS

3.1 Fixed-wing type

To shed light on the maximum speed of basic fixed-wing UAVs, we analysed 1,743 models of this type [10] (Figure 1). We also included tilt-wing UAVs in this list. Some UAVs have a tilt rotor or rotary wing alongside a wing. However, the maximum speed is reached when the rotor generates thrust while the wing generates lift force. This fact allows us to categorise these tilt-wing and tilt-rotor (with wings) UAVs in the same group, namely the fixed-wing type.

101 models of the most technically advanced UAVs were removed from the list, among them the fastest UAVs with jet, turboprop, and rocket engines [12]. The fastest model based on relatively widely accessible technology is the Berkut ISR with a piston engine. Its maximum speed is 425 km/h.

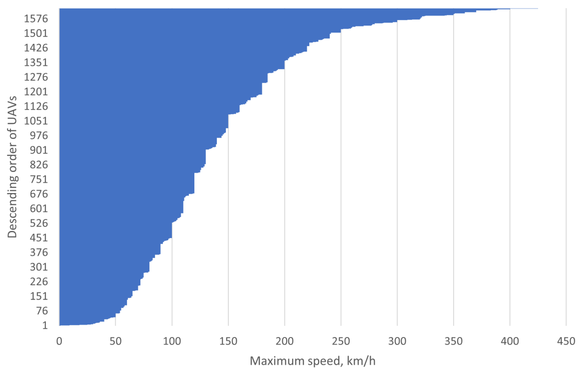

Figure 1: Distribution of the maximum speed of fixed-wing UAVs.

3.2 Rotary-wing type

We analysed and ranked 1,141 rotary-wing UAVs by maximum speed. The 5 models that we defined as highly advanced and fast were excluded from the analysis. Among these were three high-speed compound UAV helicopters: the X2, the HADA and the Jueying-8. We also excluded the Pop.Up Next and the Transporter with turbocharged engines.

After cleaning the data, we built a figure showing the distribution of the rotary-wing UAVs (Figure 2). The figure shows that the majority of the rotary-wing UAVs have a maximum speed ranging from 50 to 150 km/h. However, a Transporter UAV made by Advanced Tactics features a set of widely available technologies: a quadcopter airframe, four petroleum-powered engines, and primitive flight aerodynamics optimisation for the reduction of drag. Its maximum speed is 321 km/h, which is the maximum speed for the rotary-wing type.

3.3 Lighter-than-air type

The lighter-than-air type is exemplified by airships, which tend to have the capability to fly at higher altitudes than rotary-wing and sometimes fixed-wing aircraft. Because of

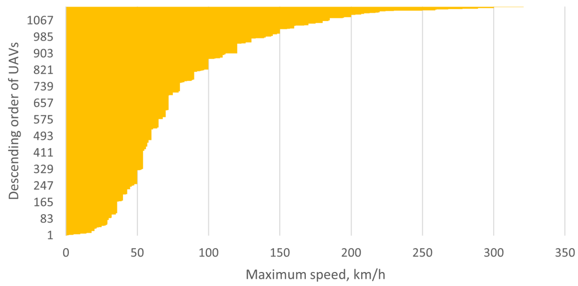

Figure 2: Distribution of the maximum speed of rotary-wing UAVs.

the low air density at altitudes higher than 4,000–6,000 metres, an aircraft can reach its maximum speed. Our study was conducted to assist U-space. Ideally, it is therefore essential to study airships' maximum speeds at a very low airspace level. Since we do not have access to such data, we estimate the airships' maximum speeds with a significant margin of safety. This approach does not affect flight safety; however, we recognise that there is room for further optimisation.

The available database of airships is not large; it only includes 27 models, the fastest of which can reach 150 km/h (Figure 3).

Not powered by engines or motors, hot air balloons are typically not classified as UAVs and are thus not included in our study.

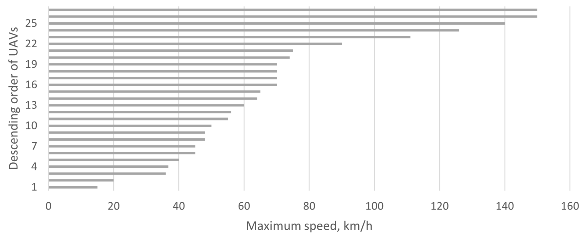

Figure 3: Distribution of the maximum speed of lighter-than-air UAVs.

3.4 Flapping-wing type

Flapping-wing UAVs are among the most rare. In our database, we only have six models, with the fastest one being capable of reaching 125 km/h (Figure 4).

3.5 Parafoil type

Parafoil UAVs, also known as powered parachutes, have a unique design that combines the capabilities of a parachute and propeller-driven aircraft. The lift force is generated by a flexible wing, while thrust is delivered by a propeller-based propulsion system. This type of drone offers a unique mix of payload capacity, stability, and ease of operation. Parafoil UAVs are the slowest of all UAV types; their maximum speed is 80 km/h (Figure 5).

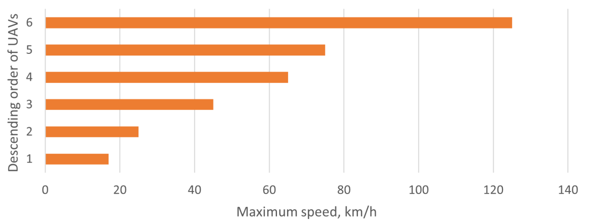

Figure 4: Distribution of the maximum speed of flapping-wing UAVs.

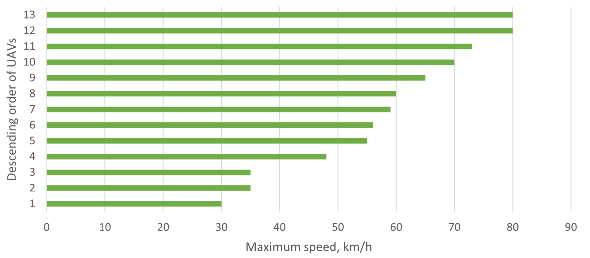

Figure 5: Distribution of the maximum speed of parafoil UAVs.

3.6 *Comparison between types*

When comparing the various types of UAVs, we see a significant difference in their maximum speeds (Figure 6). The fixed-wing aircraft, represented by the fastest type, has a maximum speed of more than 400 km/h. Close to this is the fastest rotary-wing UAV, which can fly faster than 300 km/h. Lighter-than-air and flapping-wing UAVs are relatively slow, with speeds ranging up to 150 km/h. Finally, parafoil UAVs are the slowest, with speeds not exceeding 100 km/h. The most common speeds of rotary-wing and fixed-wing UAVs differ by 100 km/h.

The fastest and the slowest types differ up to five times. It means that the classification proposed can lead to up to 5 five-fold optimisations in identifying UDUM maximum speed. Other, more rare types can achieve maximum speeds that are a couple of times slower than the Berkut.

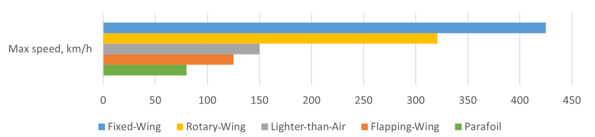

Figure 6: Comparison between types of UAVs.

Based on the global database analysis, we are able to classify a UDUM's maximum speed according to its type. In the next section, we present a mathematical model for a 4D case.

4 MATHEMATICAL MODEL

We calculate the separation distance based on a worst-case scenario to minimise the risk of collision with a known-type UDUM. In our worst-case scenario, we assume that the UDUM is the fastest model of its type and that its trajectory is optimised to collide with an ordinary U-space user. In other words, if the autonomous guidance system can plan U-space air traffic based on the worst-case scenario, the chances of a collision with a UDUM can be reduced significantly.

A collision is only possible if two UAVs have violated the minimum separation distance. To prevent the violation, it is essential to plan the CD's trajectory according to the maximum possible speed of the UDUM, which is affected by the possible range of its mass, its drag coefficient, its cross-sectional area and the lift coefficient for winged UAVs. We only analysed a global UAV database with types of UAVs and their maximum speeds (Figure 6). To predict the range of mass, drag coefficient (C_d), lift coefficient (C_l), and cross-sectional area, a global database with such data and aircraft dimensions is needed. To the best of our knowledge, such a database does not exist. Bearing this in mind, we make calculations using assumptions for the missing data.

If two UAVs are approaching the same coordinates at the same time, there is a potential risk of collision. In this light, we can measure the separation in seconds until the moment of a potential collision. A small adjustment is needed to tackle the problem of aircraft dimensions; an issue we address in the code [18] by adding two aircraft maximum dimensions and dividing the result by two. The deviations here are not very important, since we measure separation distances from the UDUM in the hundreds of metres, while UAV dimensions are only a few to several metres.

There is a significant challenge in making trajectory planning decisions for a CD when the estimated time to potential collision is several minutes. For example, a fixed-wing UAV with a maximum speed of 425 km/h can cover 212.5 km in half an hour. If a UDUM appears, will this mean that the USSP should close this radius of the U-space airspace according to the time of potential approach? As this seems unrealistic, we propose an alternative approach by measuring the time of flight termination for the CD.

4.1 *Minimum separation distance*

If the distance between the UDUM and the CD becomes less than the minimum separation distance, the CD enters an emergency state and must immediately abort the flight. If the CD is equipped with a parachute recovery system, the flight must be terminated and the time of the flight termination is a function of the height above ground level (AGL) and the parachute deployment time. If the CD has no parachute recovery system, it must conduct an emergency landing for which the time is a function of the current height above ground level (AGL), the maximum landing speed and the distance to a safe landing location.

Since the intentions and aircraft performance of UDUM remain unknown, CD cannot rely solely on superior manoeuvrability to avoid a collision with dodging manoeuvres. If UDUM is more manoeuvrable and possesses a total mechanical energy advantage over CD, there can be no guarantee of collision-free flight if UDUM's intentions are malicious.

Having innovated the MATHryoshka method, we now propose it to find the minimum separation distance, D_{ms}, between a CD and a UDUM. MATHryoshka calculates the distance to a potential collision based on flight time termination.

4.2 MATHryoshka method

The MATHryoshka method relies on a simplified, physical mass-point model of a UDUM moving at various angles γ within the range [-π/2, π/2]. At the start of the calculation, the UDUM activates maximum thrust, representing the worst-case scenario conditions.

Imagine that we have a scenario with a UDUM rotary-wing type. From our previous analysis, we know that its maximum potential horizontal flight speed is 89 m/s. Its current velocity is 10 m/s, which is detected by sensors. Its mass, cross-sectional area, and drag coefficient are given. Information on air density can be collected from U-space; in our case, we assume that it is 1.29 kg/m^3, which is a typical value at sea level.

Given

- UDUM type = rotary-wing.
- Maximum dimension of the UDUM, including width, length and height = 1.5 m.
- Maximum dimension of the CD, including width, length and height = 2 m.
- v_0 = 10 m/s.
- v_{mh} = 89 m/s.
- C_d = 0.2 - drag coefficient for a rotor-wing.
- ρ = 1.225 - air density in kg/m^3 (typical value at sea level).
- A = 0.4 - cross-sectional area, m^2.
- m = 15 kg.
- t = 10 seconds.
- e = 2.71828.
- g = 9.81 m/s2.

Task

Find the distance travelled (s) by UDUM at various γ in the range [-π/2, π/2] within ten seconds, adding the maximum dimensions of the two aircraft divided by 2. The term 'aircraft maximum dimensions' refers to the highest value among the aircraft's height, width, and length.

Solution using the MATHryoshka method

Figure 7 illustrates the vector of thrust and the primary aerodynamic forces acting on UDUM.

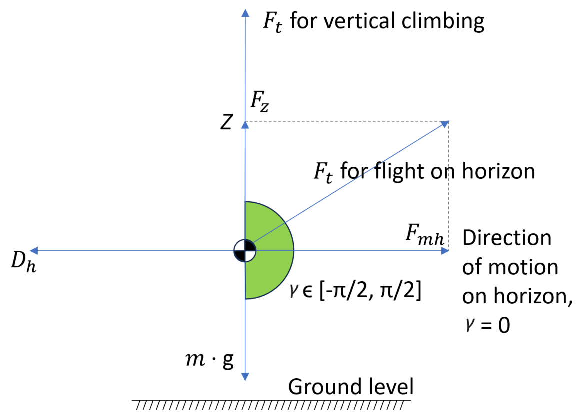

Figure 7: Vector of thrust and the primary aerodynamic forces.

- D_h – force of drag in horizontal flight with maximum thrust.
- F_{mh} – projection of maximum force of thrust on the horizontal axis X in horizontal flight.
- F_z – projection of maximum force of thrust on the vertical axis Z in horizontal flight.
- γ – flight path angle $x \in$ [-π/2, π/2].
- v_0 – initial velocity.
- m – mass.
- g – gravity.
- F_t - maximum force of thrust.

We use the next model simplifications:

- C_d is constant for any γ.
- C_d is constant at any velocity.
- Moments are ignored.

According to the Newton's law:

$$F = m \cdot a. \tag{1}$$

Where F = total force, and a = acceleration. Now, we introduce a constant b to simplify the calculus (2).

$$b = \frac{1}{2} \cdot \rho \cdot A \cdot C_d. \tag{2}$$

Where ρ = air density, A = cross-sectional area and C_d = drag coefficient. F_{mh} is constant since the UAV flies with maximum thrust in horizontal flight (3).

$$F_{mh} = b \cdot V_{mh}^2. \tag{3}$$

For horizontal flight, F_z is equal to absolute value of $m \cdot g$, consequently:

$$F_t = \sqrt{F_{mh}^2 + (m \cdot g)^2}. \tag{4}$$

The vector of velocity of UDUM can be aligned with F_t only in vertical diving or climbing. Total force generated by rotary-wing propellers acting in the direction of flight can be estimated in the following way. F_{dm} reflects thrust impact in the direction of flight. It is changing from F_{mh} (for horizontal flight) to F_t (for vertical flight). Consequently, it can be expressed as hypotenuse for both F_{mh} and F_t, depending on the respective γ values.

$$F_{dm} = \sqrt{(F_t \cdot \sin\gamma)^2 + (F_{mh} \cdot \cos\gamma)^2}. \tag{5}$$

F represents the main set of forces acting on UDUM at various flight path angles γ. As inertia and moments are not considered, F always acts in the direction of aircraft trajectory.

$$F = F_{dm} - m \cdot g \cdot \sin\gamma - b \cdot v^2. \tag{6}$$

Using the Euler method, we find the velocity and distance travelled, where s represents the distance travelled in time t at a certain angle γ (9).

$$v_{n+1} = v_n + \frac{F_{dm} - m \cdot g \cdot \sin\gamma - b \cdot v_n^2}{m} \cdot dt. \tag{7}$$

$$t_{n+1} = t_n + dt. \tag{8}$$

$$s_{n+1} = s_n + v_{n+1} \cdot dt. \tag{9}$$

To arrive at a practical solution, the next code was written in Python version 3.10.4 – see [18] for the code link. Using this code, we built Figure 8.

In the centre of the diagram, there is the UAV's centre of mass. According to various angles γ, the UDUM can travel a different distance in time t. Time t is equal to the flight termination time for the CD (we assumed it to be 10 seconds).

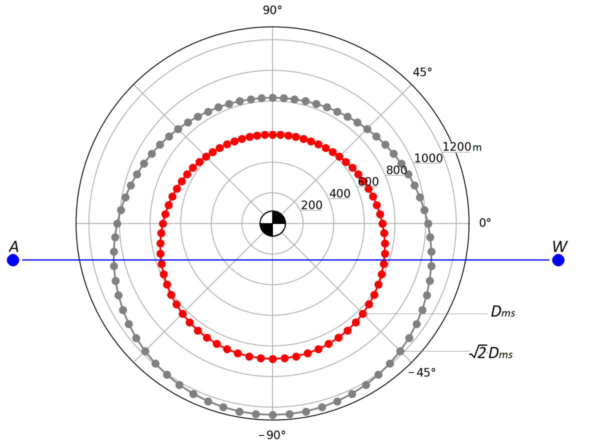

Figure 8: Distance travelled in 10 seconds for each γ, adding the maximum dimensions of the two aircraft divided by 2. Side view.

Point A represents the CD's current position, and W is the destination point. Red points represent the minimum separation, D_{ms}, which is the distance travelled by UDUM at various γ in ten seconds, plus two times the aircraft's maximum dimensions divided by 2 (see the code [18]). We consider the impact of aircraft dimensions since it is essential to mitigate the collision threat.

The grey points represent the safety radius, which is D_{ms} multiplied by $\sqrt{2}$ (13), as we explain in the next section.

4.3 Minimum separation distance and safety area

One of the key issues in avoiding collisions with UDUMs is the uncertainty regarding their intentions and the lack of information about aircraft performance, including unknown limitations on flight characteristics. The current vector of velocity of a UDUM is essential for tactical deconfliction. Also, the data on UAV performance should be collected in a global UAV database, which, as far as we are aware, does not exist yet. The current vector of velocity is not very reliable since it can change depending on different accelerations and dynamics due to the huge diversity among UAV flight characteristics [19]. In light of these limitations, we propose a multifactor approach that incorporates UDUMs' maximum speed, mass, drag coefficient, cross-sectional area, current vector of velocity and geometric optimality.

Consider a situation where a CD intends to fly from point A to a destination, point W (Figure 9). For simplicity's sake, we assume that the CD and the UDUM are at the same altitude. The direct flightpath of the CD intersects with the safety area around a UDUM that has a radius denoted as r (10). The position of the UDUM is known and presented in point I (Figure 9).

$$r = \frac{D_{ms}}{\cos\sigma}. \tag{10}$$

A safety area with radius r around point I is essential to ensure an optimal distance between the CD and D_{ms} (Figure 9) at the moment of approach. The optimal distance is the safety area with radius r, which is equal to the IG segment. There is a fundamental problem in determining the value of r. From one perspective, it must be long enough to maximise the right angle σ – the greater the angle, the less the chance that a new random vector of velocity of the UDUM will be threatening the CD. From another perspective, IG must be sufficiently short to reduce the travelling distance of the CD. Measuring G as a point that the CD can reach faster than the UDUM, based on the current vectors of velocity, is not reliable since the UDUM may have the potential to accelerate or decelerate. If we rely on the UDUM's maximum speed, which is higher than that of the CD, there are instances where point G cannot be found at all. Even employing the standard separation distance between CDs defined by regulation cannot guarantee collision avoidance since the intention of the UDUM is unknown and may even be malicious.

Consequently, we propose to use a geometric optimality logic to find the r value. There are two values that are interconnected (10) – angle σ and value r, since lines $u_1 \perp s$ and $ID = IF = IC = D_{ms}$. Also, $s_1 \parallel s$, $u \parallel u_1$, $C \cap s_1$, $C \cap u$, $F \cap t$, $D \cap u_1$, $D \cap s$, $G \cap n_1$, $G \cap t$, $G \cap s_1$, $G \cap u_1$.

The greater angle σ is, the less potential of collision since the intentions of the UDUM are unknown. Conversely, the greater the value of r, the more U-space airspace is covered by the safety area and the longer distance the UDUM will have to cover to come to W through G. For the sake of optimality, it is essential to determine a value of σ that maximises the ratio of σ to r. In that pursuit, we should find a derivative of r and a value of σ that maximises the ratio.

$$\frac{d}{d\sigma}\left(\frac{D_{ms}}{\cos\sigma}\right) = \frac{D_{ms}\cdot\sin\sigma}{\cos^2\sigma}. \quad (11)$$

$$\frac{D_{ms}\cdot\sin\sigma}{\cos^2\sigma} = D_{ms}\cdot\frac{1}{\cos\sigma}. \quad (12)$$

In any case, $\sigma \in (0, \frac{\pi}{2})$, thus the equation (12) is true when $\sigma = \frac{\pi}{4}$, thus $\frac{1}{\cos\sigma} = \sqrt{2}$, which gives the equation (13).

$$r = \sqrt{2}\cdot D_{ms}. \quad (13)$$

The geometric approach may be subject to criticism because it assumes that changing σ is similarly important for trajectory planning as changing the r value. In fact, both are essential, though probably not equally so. We acknowledge the potential for further optimisation in this area.

We disregard an error factor that could be essential for addressing delays associated with data collection, computation, and transfer. The error factor may potentially increase the safety radius required.

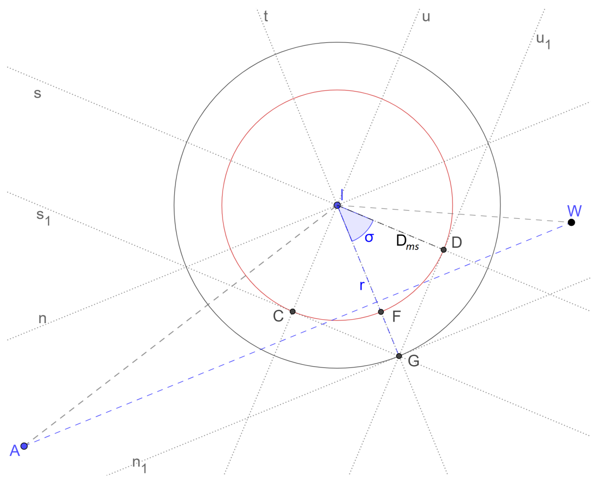

Figure 9: Minimum separation distance and safety radius for γ = 0°. Above view.

In this section, we analysed the scenario where the CD and the UDUM are at the same altitude, which for the worst-case scenario is γ = 0°. However, in actual airspace, altitudes are likely to differ, for example when the altitude of a UDUM is higher than that of a CD (Figure 10). Nevertheless, following the same logic, we can multiply D_{ms} by $\sqrt{2}$ to find the safety radius for each value of γ (Figure 8). For example, for γ = -45°, D_{ms} = 833.5m and r = 833.5m $\cdot \sqrt{2} \approx$ 1179m.

4.4 Some typical scenarios

First, it is essential to identify if the UDUM moves to the location of the CD with the risk of penetrating the safety area. This means that the algorithm of the autonomous guidance system must check if the projection of the vector of velocity of the UDUM, **u**, belongs to the angles ρ_1 or ρ_2 (Figure 10). If **u** belongs to ρ_1 and not to ρ_2, we suggest to avoid collision by choosing a flight path that is closer to point K than point T.

To simplify calculations, we moved the X and Y axes in a way such that (see Figure 11):

- Point $A \in Oy$. Vector $\mathbf{u} \parallel$ axis Ox. For 3D airspace, **u** is a vector projection of the vector of velocity of the UDUM on the horizontal plane with points OAW.
- Points L, R, $N \in Ox$.
- Ox is a tangent line to the safety circle (with radius r) in point N.
- q and t_1 are the tangent lines to the safety circle with radius r.
- $t_1 \parallel t_2$.

If $\mathbf{u} \in \rho_2$ and $\mathbf{u} \notin t_2$ (Figure 11), the waypoint L is a special point that allows the CD to effectively leave the

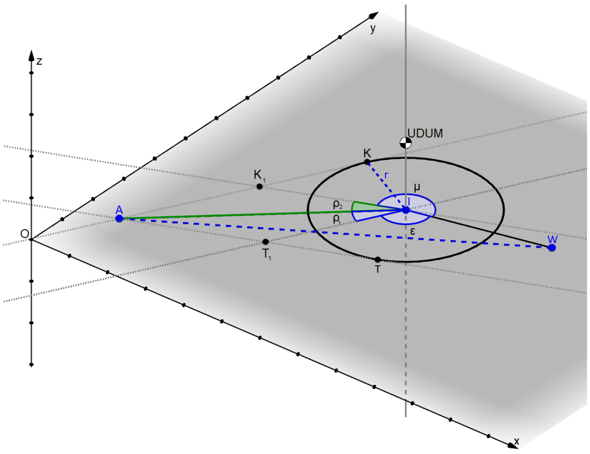

Figure 10: Front collision hazard, UDUM is higher than CD. Two o'clock view angle.

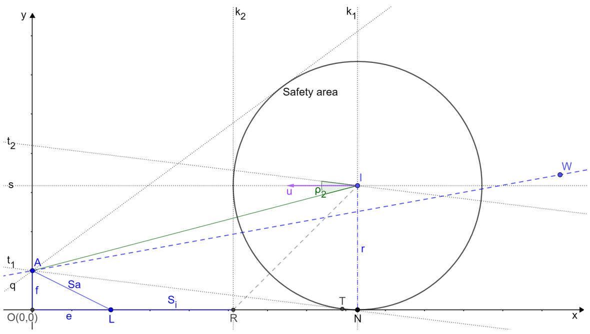

Figure 11: Rho two problem. Above view.

UDUM's direct flightpath, thereby avoiding the safety area of the UDUM. Effectively means that if the two aircraft should move with the same vector of velocity, the CD will reach point L. At the same time, point R will have the same coordinates as L since the UDUM moves in the same direction. Upon reaching point L, the CD is not at risk of violating the minimum separation distance if the UDUM continues its movement in the same direction and the CD continues its flight to point N. In the next section, we provide a solution for finding the coordinates of point L.

4.5 Rho two problem

Task conditions. Given

- $A(0, y_a)$ – location of the CD.
- $f = y_a$.
- $I(x_i, y_i)$ – projection of location of the UDUM on the horizontal plane OAW.
- $W(x_w, y_w)$ – location of the destination point of the CD.
- r – the safety radius (13).
- **u** – a vector projection of the vector of velocity of the UDUM on the horizontal plane OAW.
- V_i – the projection of the velocity of the UDUM on plane OAW.
- V_a – the velocity of the CD.
- The CD and the UDUM are in simultaneous flight.
- t_1, q – the tangent lines between point A and the safety circle with centre I and radius r.
- $t1 \parallel t2$.
- ρ_2 – the angle between line AI and line t_2.
- μ - the exterior angle at the points K_1, I, W.
- ϵ - the interior angle at the points T_1, I, W.
- $\mathbf{u} \in \rho_2$ and $\mathbf{u} \notin t_2$.
- Line $OLRN \parallel \mathbf{u}$.
- Line $OLRN$ is a tangent line to the circle with radius r and centre I.
- $RN = IN = r$.

Task

Find x coordinates of point L.

Solution

$$x_r = x_i - r. \tag{14}$$

S_a is the travelling distance of the CD from point A to point L, $OR = j, OL = e, AL = S_a$.

$$e = \sqrt{S_a^2 - f^2}. \tag{15}$$

Since V_i and V_a are known, its ratio k is a constant. S_a is a distance AL, and S_i is a distance RL.

$$\frac{V_i}{V_a} = \frac{S_i}{S_a} = k. \tag{16}$$

$$j - kS_a = \sqrt{S_a^2 - f^2}. \tag{17}$$

$$(k^2 - 1)S_a^2 - 2jkS_a + (f^2 + j^2). \tag{18}$$

$$x_l = e = \sqrt{S_a^2 - f^2}. \tag{19}$$

For $S_a > f$, $V_i > 0$. If $V_a \neq V_i$, $k \neq 1$, S_a and S_i can be intersected at two points on the line x, thus:

$$S_a = \frac{2jk \pm \sqrt{(-2jk)^2 - 4(k^2 - 1)(f^2 + j^2)}}{2(k^2 - 1)}. \tag{20}$$

However, for the sake of optimality, the smallest positive value of x_l is needed, thus:

$$x_l = \sqrt{\left(\frac{2jk - \sqrt{(-2jk)^2 - 4(k^2-1)(f^2+j^2)}}{2(k^2-1)}\right)^2 - f^2}. \tag{21}$$

If $V_i > 0$ and $f > S_a$, the CD is at risk of penetrating the UDUM's safety area wherever the CD flies. Mathematically, this means that the discriminant cannot be negative. It means that solutions exist for:

$$k < \sqrt{1 + \left(\frac{j}{f}\right)^2}. \tag{22}$$

If $V_a = V_i$, thus $S_a = S_i$, and $k = 1$, thus:

$$(j - S_i)^2 = S_i^2 - f^2. \tag{23}$$

$$S_i = \frac{j^2 + f^2}{2j}. \tag{24}$$

$$x_l = j - \frac{j^2 + f^2}{2j}. \tag{25}$$

If $V_i > 0$ and $f = S_a$, thus:

$$x_l = 0. \tag{26}$$

If $V_i > 0$, then vector **u** = 0, consequently, point R cannot be defined. We suggest heading to point T in this case; however, that is a different task.

If $\mathbf{u} \in \rho_1$ and $\mathbf{u} \notin \rho_2$ and $\mathbf{u} \notin \varepsilon$ (Figure 10), and AW intersects with the safety area, the task can be solved in a similar way, but by ensuring that the CD heads to the other (right) side of the UDUM.

We assume that the velocity vector of the UDUM and its projection **u** are known in real time. Therefore, recalculating point L every few milliseconds (for example) could move its coordinates to a new safe position if the UDUM accelerates. Point L can also be moved to a more optimal position if the UDUM decelerates during the flight.

If $\mathbf{u} \in \mu$ or $\mathbf{u} \in \varepsilon$ and AW intersect with the safety area, other challenges arise in which the minimum separation distance D_{ms} and the safety radius r play significant roles in defining the problem and finding a suitable solution. Another example is when AW does not intersect with the safety area (Figure 12), but there is a potential risk that the minimum separation distance may be breached if the UDUM is fast enough. A_1 is the position of the CD, and W_1 is the position of the UDUM. A_1T_2 and W_1T_1 are tangent lines to the circle of the safety area. $A_2I_1 \parallel A_1T_2$, $T_1W_1 \parallel I_1W_2$. $\mathbf{u}_1 \in \rho_3$.

To solve such a task, we need to know the minimum separation distance, D_{ms}, and the safety radius, r.

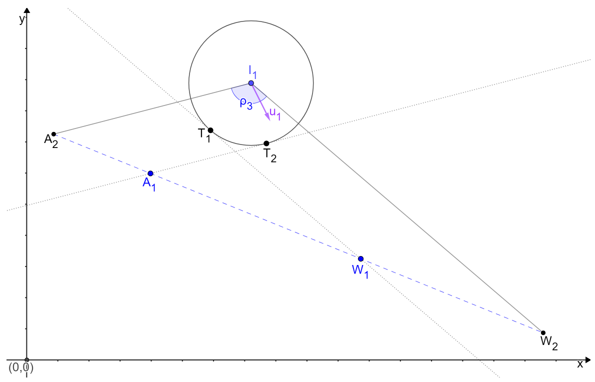

Figure 12: Trajectory intersection in case of remote positions. Above view.

5 CONCLUSION

This article proposes a novel method for calculating the minimum separation distance and the safety radius for a UDUM whose type was identified by an image. The method includes global UAV database analysis, classification of the existing drones, determination of the fastest UAVs among types, and a mathematical model for estimating the safety radius and the minimum separation distance. To make the method available for the autonomous guidance system, we suggest creating a global UAV database that would allow us to predict the range of drag coefficient, lift coefficient (for UAVs with wings), mass and cross-sectional area based on UAV dimensions.

Relying on the method and the assumptions made, we solved the challenge of collision avoidance when a UDUM approaches a CD, posing a risk of infringement of the minimum separation distance. We also discussed the typical collision hazard patterns for which the method can be used in future research. To quantify the method, we suggest performing the appropriate experiments in a simulated environment.

The continuous development of UAV technologies underscores the importance of maintaining an updated global UAV database. Such an approach could assist in measuring minimum separation distances by using the latest advancements in widely available modern technologies. In this light, the study on UDUM type identification by image or video looks promising.

The findings show that the suggested method allows us to deal with UDUMs whose types were identified by the recognition system. The recommended separation distances measured in hundreds of metres appear realistic and feasible. The significant differences in the maximum speeds among the various types of UAVs reflect the optimisation of the problem.

In case the recognition system cannot identify the UDUM's type, the UDUM can be classified as the fastest type to guarantee flight safety.

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