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RESEARCH ARTICLE

Quantifying Well Clear for Autonomous Small UAS

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ABSTRACT Air traffic safety is the primary concern when it comes to the integration of Unmanned Aircraft Systems in the civil airspace. At the tactical level, the goal is to quantify en-route safety through pairwise separation minima. Unmanned Aircraft Systems make use of Detect and Avoid systems to remain, or regain well clear from other aircraft. There is already a well clear definition adopted for large Unmanned Aircraft Systems, however, this definition is not adequate and applicable to small Unmanned Aircraft Systems operating in low altitudes. In order to ensure the safe separation of various types of sUAS with different performances, a self-separation method is proposed. The method is based on dynamic protection zone, an early concept developed by US Air Force and later adapted into a time-based Detect and Avoid self-separation method. This paper outlines an engineering approach on designing a generic methodology, to define well clear among small Unmanned Aircraft Systems. For this purpose, both unmanned aircraft and systems performance are considered. Furthermore, we specify and recommend appropriate well clear thresholds and Detect and Avoid alerting times, based on the results the severity of loss of well clear. Several influencing factors such encounter geometry, speed and uncertainties in Communication, Navigation and Surveillance systems are examined to obtain efficient separation criteria.

INDEX TERMS Conflict management, detect and avoid, self-separation, small UAS, well clear.

NOMENCLATURE

τ	Tau, an approximation of T_{CPA}
τ_{mod}	Modified Tau or DAA Time Threshold
ATM	Air Traffic Management
CPA	Closest Point of Approach
DAA	Detect and Avoid
LoS	Loss of Separation
RWC	Remain Well Clear
SAA	See and Avoid
T_{CPA}	Time to CPA
UTM	Unmanned Aircraft System Traffic Management
WCV	Well Clear Volume
WCA	Well Clear Area
WCR	Well Clear Recovery

I. INTRODUCTION

The global market of commercial and civil applications of unmanned aircraft systems (UAS) is projected to grow significantly, with the European UAS industry expected to exceed €10 billion annually by 2035, and over €15 billion by 2050 [1]. Most of the market value is predicted to lie in the operations of small UAS (sUAS)¹ at the very-low-level airspace (VLL) — specified in [2], [3] as the volume of air under 500 ft above ground level (AGL) — because of the characteristics of the majority of missions and the application fields of interest [4], [5]. Moreover, the growing trend will be accompanied by increased density and new challenges, mainly related to safety, reliability and efficiency of the airspace management. Therefore, to successfully deploy UAS operations, it is paramount to develop and implement UAS

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¹Unmanned Aircraft Systems(UAS) weighing less than 25 kg.

Traffic Management Systems (UTM) — analogous to Air Traffic Management (ATM) in manned aviation [6], [7].

Focusing on safety, a crucial concern is the risk for potential conflicts between UAS, which can lead to mid-air collisions if the conflicts are not mitigated in time. Essentially, a *conflict* refers to a state or situation where a predetermined *separation minima* may be compromised by two or more aircraft [8]. The event when the separation minima is infringed is called a *loss of separation* (LoS). To prevent a LoS, UAS make use of *separation provision* (i.e. a possible UTM service), which is a tactical process for keeping aircraft away from hazards by at the least the appropriate separation minima [8]. When UTM services fail and a UAS determines it is still in conflict, a *self-separation* maneuver is taken. The self-separation is a function carried out by the UAS Detect and Avoid (DAA) system and intended as means of compliance with regulatory requirements to remain *well clear* of other airborne hazard [9]. The Detect and Avoid capabilities are illustrated in Fig.1. Nominal DAA capabilities comprise three main modules: Conflict Detection, Alerting and Conflict Resolution. A core concept lies on the estimation of closest point of approach (CPA) between two aircraft. CPA is characterized by time to CPA and distance to CPA. The time to CPA is referred to as the range tau (τ) and is an approximation of the time, in seconds, to CPA. τ is defined as the ratio of the slant range with the closing speed between two aircraft. While this definition is quite simple, it leads into some issues, especially when there are encounters with very low and/or very high closure rates [10]. For instance, in a slow overtaking encounter, the intruder can get very close in distance, without any tau range infringement. To remedy these type of problems, a modified version of tau is used, referred to as tau mod (τ_{mod}) and defined as following [11]:

$$\tau_{mod} \equiv -\frac{r^2 - DMOD^2}{r\dot{r}} \quad (1)$$

DMOD is a modified distance designed to comply with manned aviation collision avoidance systems; r and \dot{r} corresponds to slant range and closure rate respectively.

These metrics are commonly used to define a conflict and to determine alerting level and resolution maneuvers. Once a conflict is determined the DAA capabilities offer three resolution functions (services): Remain Well Clear (RWC), Well Clear Recovery (WCR) and Collision Avoidance (shown with yellow, orange and red respectively). The difference between this functions is based on the objective, triggering event and maneuver behaviour. The triggering events can be thought as thresholds when a particular function should be activated. For instance, if two sUAS are closer than a specified RWC threshold, a maneuver should initiated as soon as possible to prevent an infringement of Well Clear boundary. In addition, DAA offers situational awareness in form of cascade alert levels depending on the risk severity. A more detailed explanation on DAA capabilities is given in section II.

Despite ongoing research in conflict management for medium-large UAS, the up-to-date separation methods and criteria (i.e. separation minima) are not adequate for operations in VLL airspace and sUAS-sUAS encounters [9], [13]–[15]. This is mainly a result of diverse small UAS types (i.e., multi-rotor, fixed-wing), their performance capabilities (i.e., size, maximum take-off weight, maximum airspeed), airspace structure, and unreliability in Communication, Navigation, and Surveillance (CNS) [16], [17].

In this work we specify and recommend adequate values of well clear threshold & DAA alerting times for sUAS-only encounters. For this purpose, we adopt and extend a dynamic protection zone concept as separation method, based on [18], and use it to characterize dynamic well clear (WC) boundaries suitable for sUAS. The well clear boundaries define a safety volume (e.g. cylinder) such that sUAS pairs not occupying this volume simultaneously, are said to be well clear. This approach requires dynamic thresholds based on the performance of the aircraft, for instance, UAS with high maneuverability require smaller separation minima. Nevertheless, in their work [18] they do not consider the affects coming from the DAA systems and other uncertainties that influence sUAS operations, to which we consider as key components.

To verify the well clear threshold specifications and to study the effects that uncertainties (such communication delays, wind estimation errors, and navigation errors) have in the relationships of our metrics, we run closed-loop fast simulations in ICAROUS.² We assume that ownship sUAS is equipped with DAIDALUS [19] as a DAA method and the intruder traffic continues in straight line through the encounter, i.e. $V_i = \text{constant}$ and turn rate $\omega_m = 0$ rad/s. We found out that the dynamic well clear thresholds can ensure safety and be more efficient compared to previously adapted well clear definitions for medium-to-large UAS.

The rest of this work is structured in the following way: Section II contains some background regarding traffic management. Section III summaries related works. In Section IV, we introduce the methodology and experimental setup. This is followed by a discussion of the results in Section V and a summary of the conclusions and future work in Section VI.

II. BACKGROUND

This section describes the current conflict management in manned aviation and introduces a framework of a UAS conflict mitigation system based on ICAO, NASA, FAA, U-Space, as the main reference works. The analyzed UAS conflict management framework is considered an evolution of the present ATM system's conflict management levels. Furthermore, we attempt to clarify the different concepts used in this paper, such as Detect and Avoid (DAA), separation methods and well clear concept.

²<https://github.com/nasa/icarous>

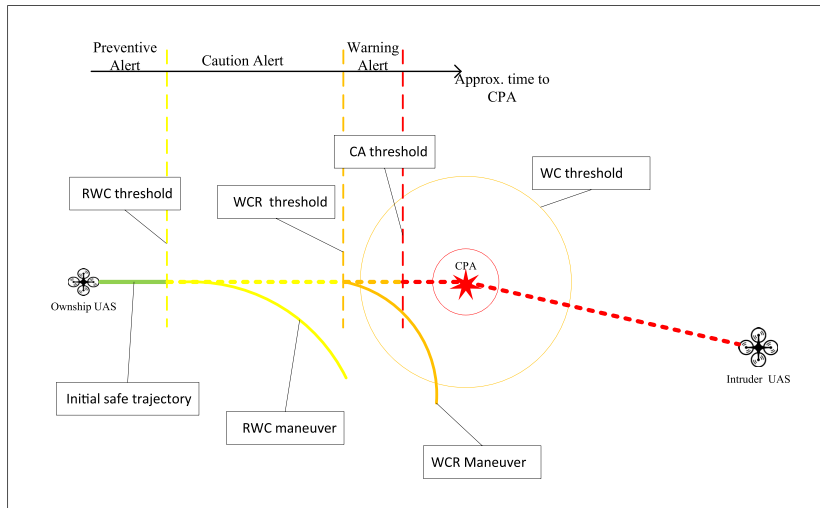


FIGURE 1. DAA capabilities, based on [9], [12].

A. TRADITIONAL AIR TRAFFIC MANAGEMENT (ATM) SYSTEMS

According to the ICAO Doc9854/AN458, the function of conflict management is to limit, to an acceptable level, the risk of collision between aircraft and hazard. Conflict management, defined in ICAO and illustrated in Fig. 2, consists of Strategic Conflict Management, Tactical Conflict Management (e.g., separation provision) and Collision Avoidance (CA). The former addresses mainly pre-flight procedures to mitigate conflicts based on the flight plans and aims to reduce the workload for tactical interventions. However, there are cases that strategic actions might be required after take-off, particularly in long-duration flights. The tactical level is responsible for mitigating midterm conflicts through gentle maneuvers in a timely fashion, also known as the separation provision function. In case that separation provision is compromised, CA is activated, which identifies short-term (imminent) intruders and performs last-resort maneuvers to prevent mid-air collisions.

In manned aviation, tactical conflict management is issued by Air Traffic Control (ATC), a centralized ground-based system that provides guidance and information to the pilots through Air Traffic Control Operators (ATCo). In the event of an emerging collision, Collision Avoidance System (CAS) is enabled seconds before closest point of approach (CPA). Traffic Collision Avoidance System (TCAS) [20] and Airborne Collision Avoidance System (ACAS) are standard CAS systems mandatory for most commercial aircraft, and their main objective is pairwise collision avoidance [21]. The closure rate of aircraft, encounter geometry, and flight level are the primary factors that affect their performance. In addition, the See and Avoid principle serves as a CA method, particularly for operations in uncontrolled airspace and general aviation, which might not be equipped with TCAS or similar systems. In such cases, the pilots are fully responsible for

searching and avoiding potential conflicting aircraft under specified rules [22].

B. UAS TRAFFIC MANAGEMENT

UAS traffic management follows similar safety layers as ATM: strategic conflict management, separation provision, and collision avoidance. Note that UTM is responsible also for mitigating conflicts caused by some extra types of hazards/risks, such as no-fly zones (i.e., airport areas), manned aircraft, terrain, and static obstacles. For illustration purposes, we focus on sUAS conflict management framework (the framework itself is not necessarily limited to the small UAS) that deals only with airborne conflicts. This framework aligns with SESAR/NASA-UTM concepts [23], [24] and spans four stages that assess all the safety layers mentioned above. First, to describe the framework, we follow a similar approach as in [25], which gives a simple explanation in an end-to-end process, covering all the stages of conflict mitigation applicable in sUAS operations. Next, we introduce plausible metric values synthesized by literature review, the verification of which lies in the scope of this work. Finally, we interpret the functions related to conflict management and map them to the respective safety stages (layers).

The proposed framework comprises four stages, referred to as Strategic Conflict Mitigation (while in various works, including some ICAO [26], conflict mitigation is referred to as Deconfliction, we choose to use the term Mitigation in this work to maintain consistency), Separation Provision Service, Self-Separation, and Collision Avoidance.

Stage 1 - Strategic Conflict Mitigation (CM): conflicts are detected and resolved before take-off based on their flight plans submitted to the UTM. This process invokes removing intersecting trajectories on spatio-temporal basis and engaging re-planning to align with various constraints such as no-fly zones (e.g., airports), weather, and other obstacles.

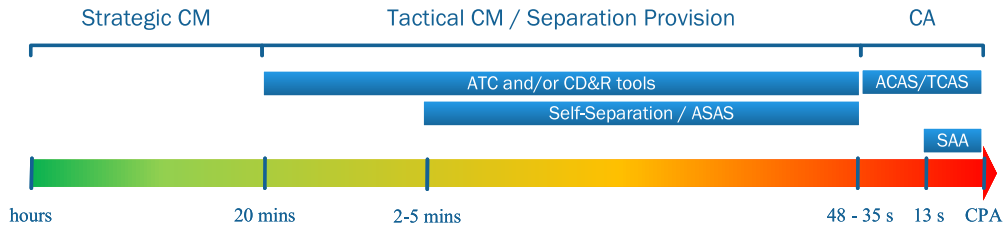


FIGURE 2. ATM Conflict Management time-frames.

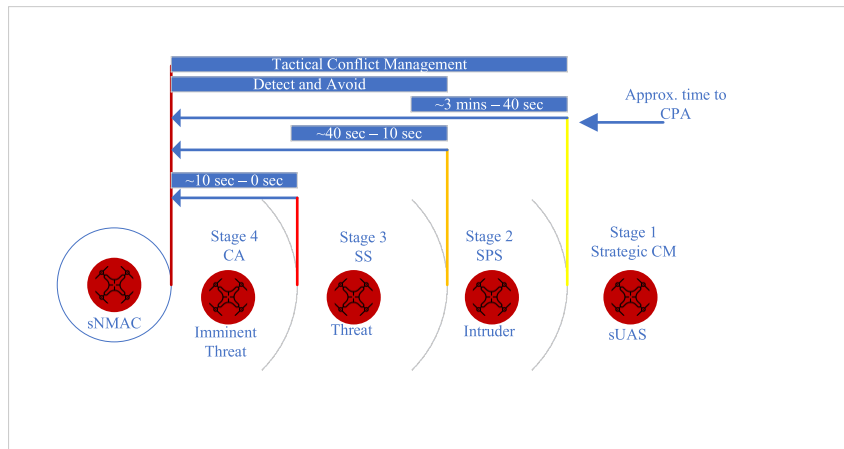


FIGURE 3. sUAS Conflict Management framework derived from [24]–[26].

Stage 2 – Separation Provision Service (SPS): Similar to the ATC functionalities, UTM has to offer in-flight separation as a service if the flight plans approved in stage 1 are not conflict-free during the flight. The sUAS subscribed to this service [27], gets early awareness (i.e., alarms) for possible loss of separation between other aircraft (manned/unmanned) and guidance for safe and efficient resolutions for planned operations.

Stage 3 – Self-Separation (SS): Derived from the Free Flight concept [28], relies on the sUAS capabilities to maintain a safe separation minima from other airspace users. This functionality can be carried manually by the remote pilot (RP), assisted, or fully automated. Still, it removes the responsibility of conflict mitigation from the UTM and delegates it to the sUAS.

Stage 4 – Collision Avoidance (CA): provides a final safety layer to prevent mid-air collisions. It is characterized by imminent and sharp maneuvers (or getting into a hovering state) and can be managed by the remote pilot or autonomously as well [29].

The Fig. 3 illustrates the general framework for managing sUAS conflicts. Here, the stages from 2 to 4 deal with tactical conflict mitigation. Stage 2 is seen as a ground-based service, which requires reliable communication between the sUAS and the UTM (e.g., U3 services of U-Space [30]). In the case of a mid-air intruder that is not resolved by stage 2, the ownship sUAS must use Detect and Avoid (DAA) capabilities to resolve a potential collision.

A typical DAA system is composed of CNS subsystems, sensors, conflict detection module, alerting and guidance algorithms, ground control station and command and control (C2C) subsystems. In Fig. 4 we show a block diagram for a plausible autonomous DAA system for sUAS.

In case of autonomous flights, the navigation and maneuvers are made possible by the use of a flight computer, referred to as the autopilot (AP). Each one of these components adds a delay lag in the overall time response of a particular DAA system, which directly effects the quantification of the separation minima (e.g. remotely guided sUAS must take in consideration human factor, which adds a specific t seconds delay).

C. SEPARATION METHODS

According to ICAO separation method (i.e., separation mode) refers to a set of approved rules, procedures and conditions associated with the separation minima [8], also referred to as separation threshold in this paper. While estimating threshold values, various factors are considered, such are UAS characteristics (e.g. size), performance (e.g. ground speed, turning rate) and an acceptable collision risk level [31]. There are three types of separation thresholds applied in UAS missions: distance-based, time-based, and a combination of both, time-distance-based.

Distance-based separation threshold is the simplest and can be seen as a spatial boundary around the aircraft, e.g., a cylindrical volume with height H and radius R , if which is

infringed by an intruder, a loss of separation has occurred. A drawback of this approach is not taking in consideration the intruder speed, in an explicit way.

A time-based separation on the other hand, takes into account the relative speed of UAS (i.e. closure rate) by calculating time to the closest point of approach (T_{CPA}). If the estimated T_{CPA} is less than a predetermined time threshold, it is considered as a loss of separation event [32], [33].

Lastly, a time and distance based separation, combines the advantages of both metrics and has become the tendency of defining safe separations in UAS.

D. THE WELL CLEAR CONCEPT AND NEAR MID AIR COLLISION

The concept of well clear has been proposed as an airborne separation standard to which an DAA system must adhere [34]. The DAA system spans both functions of stage 3 and stage 4 and can be implemented on-board of sUAS and/or on the ground, as illustrated in Fig. 3.

The notion of WC is mentioned by FAA-defined Vision Flight Rules (VFR) and used in ICAO Annex 2 Rules of Air, but neither of them provides an exact definition for the concept, nor specifies any minimum separation threshold. Defining well clear for UAS is challenging because of the need to quantify a separation standard that is determined subjectively by pilots. If WC threshold is too small, unacceptable collision risks could arise. On the other hand a large threshold could impact the airspace system in various ways (e.g. capacity). Therefore, the challenge is to find an acceptable definition and quantification that ensures safety while minimizing operational impacts.

While there is no standard definition of well clear, two main functions are associated with this state: *Remain Well Clear* (RWC) and *Well Clear Recovery* (WCR). In terms of tactical conflict management, RWC is equivalent to the self-separation function (i.e. stage 3 of the proposed CM framework), which aims to prevent a loss of WC to occur through smooth maneuvers that consider several factors (e.g. safety, operational, mission) [36]. *Well Clear Recovery* (WCR) is a function activated seconds before an unavoidable loss of WC and/or when an actual loss of WC occurs. In this situation DAA systems should give directive maneuvers, such that the sUAS regains its previous state. Both of these functions are related to a well clear notion, which is mainly viewed as protection volume around UAS, referred to as well clear volume (WCV) [9], [37], [38]. This volume can be specified by spatial thresholds, temporal thresholds, or both at the same time, referred to as separation minima in this work.

In addition, the near-mid-air-collision (NMAC)³ represents the last safety volume. As the name suggests, a distance smaller than NMAC represents a very severe loss of well clear that could result in a collision in the worst case. This distance is usually defined based on the dimensions of the UAS and its navigation performance [39].

E. DAIDALUS: A REFERENCE DAA METHOD

Detect and Avoid Alerting Logic for Unmanned Systems (DAIDALUS)⁴ is a software library that implements a configurable DAA concept intended to support the integration of UAS into civil airspace [19], [38]. The core services provided by DAIDALUS are situational awareness through alerting logic, conflict detection (CD) and maneuver guidance. It is intended in aiding to maintain WC status via RWC maneuvers, and WCR in case the WC status is lost [19]. To do so, DAIDALUS uses linear projections of both ownship and intruder in a given look-ahead time T .

The DAA alerting logic is to provide critical timing information to the RP and/or to an autonomous system, regarding a potential loss of WC with a conflicting aircraft [40], [41]. The alerting algorithms utilized in DAIDALUS span three level of redundancy based on the projected time to loss of WC (LoWC), within T :

- Predictive, intended for monitoring and situational awareness. No actions are taken at this level.
- Corrective, requires immediate awareness and a subsequent response from RP and/or autonomously to prevent a loss of WC. In this paper it is considered as a time-based self-separation threshold (see Fig.2) and is associated with RWC function.
- Warning, indicates a loss of WC, therefore an immediate response is required. In our model it corresponds to WCR function.

In the CD logic, DAIDALUS uses parametric WC volumes to determine well clear status between pair of aircraft. The WC volumes are easily configured and serve as separation minima for computing maneuver guidance. Maneuvers can be suggestive to help the remote pilot and/or directive in more severe situations, i.e. WC recovery.

III. LITERATURE REVIEW

In this session we discuss the state of the art related to self-separation methods and standards applied to UAS and sUAS operations. We attempt to give a chronological perspective to show the improvements in this field. Moreover, we present the gaps and limitations, which served as motivations for this paper and an overview of the to date DAA systems.

In order to quantify a self-separation standard (i.e. self-separation minima and method) for sUAS two main approaches are identified based on an extensive literature review. The typical method, which is adopted for the development of RTCA and ASTM DAA standards, is based on unmitigated collision risk analysis. A well clear separation is defined as relative separation where a desired unmitigated risk threshold is achieved. The evaluation is done based on simulated Monte Carlo encounters that take in consideration representative flight trajectories and environmental uncertainties (e.g., wind). The other method is based on defining safe separation boundaries around UAS, generally

³here referred as small NMAC (sNMAC) to indicate the UA category.

⁴<https://github.com/nasa/daidalus/tree/v2.0.1>

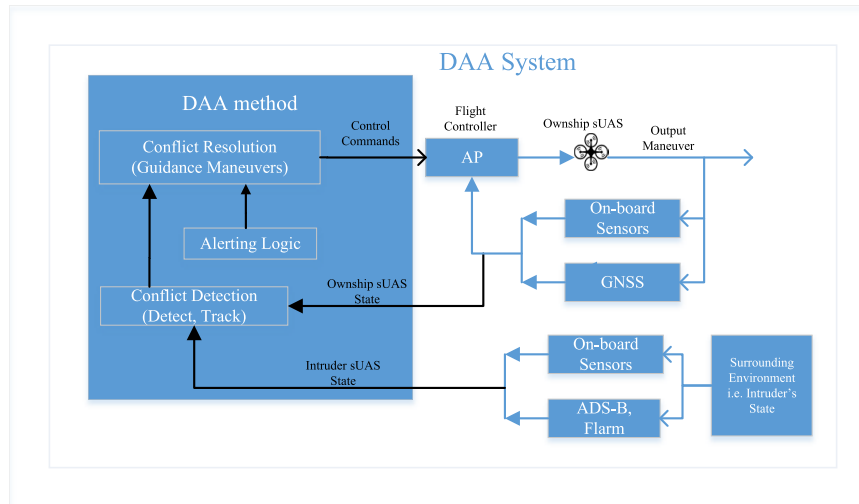


FIGURE 4. sUAS DAA system block diagram based on [19], [35].

characterized by the UAS performance, operational constraints and related uncertainties. UAS performance includes aircraft maneuver capabilities, CNS uncertainties and other associated systems performance such as a DAA system. This method tends to model the behavior of each component and requires unique separation boundaries with respect to the UAS. For instance, a fixed-wing UAS would have a different safety boundary compared to a quad-rotor. Each component affecting this safe boundary has different impacts in horizontal and vertical separation criteria. A good example is the difference in the dynamics between horizontal and vertical maneuvers. Moreover, sensor accuracy, flight controller behavior, wind influence and so on, change on how they affect the aircraft in the horizontal and vertical dimensions. Therefore, to quantify a WC volume the horizontal and vertical criteria are studied separately.

A. WELL CLEAR AS SELF-SEPARATION STANDARD BASED ON UNMITIGATED COLLISION RISK ANALYSIS

In the last decade there has been a lot of effort to define and quantify Well Clear as self-separation standard that can be applied to UAS, sUAS, and other Advanced Air Mobility (e.g. Urban Air Mobility). Wiebel *et al.* make an important case of using and defining WC based on an acceptable collision risk value [42]. According to this work, the separation standard may vary according to what the regulator entities consider an acceptable risk level of a NMAC occurring, given the relative state of a pairwise encounter. The model takes in consideration TCAS alerting criteria and recommends a 8000 ft threshold for head-on encounters and 3000 ft for track-crossing and/or overtaking encounters.

In 2013, the Second Caucus of the FAA Sense and Avoid Workshop endorsed the idea that WC for UAS is a separation standard and recommended for it to be time-based (i.e., number of seconds prior to near mid-air collision) in the horizontal plane, and distance-based in the vertical

plane [43]. The workshop considered three UAS well clear concepts by NASA, MIT LL, and Air Force Research Laboratory [31]. Based on the conclusions and recommendations of the workshop, in August 2014 Unmanned Aircraft System (UAS) Executive Committee Science and Research Panel (SaRP) and the Radio Technical Commission for Aeronautics (RTCA) Special Committee 228, defined well clear as a volume that relates a modified tau (τ_{mod}) value of 35 seconds with a distance threshold (both a minimum distance and horizontal miss distance filter) of 4000 feet in the horizontal plane. The vertical Well Clear definition was determined by a fixed distance from the ownship of 700 feet [44].

Munoz. *et al.* [45] brought a formal definition for Well Clear, by giving a mathematical foundation for the concept, based on TCAS II logic and ICAO principles. His work progressed with the implementation of a set of DAA algorithms, known as DAIDALUS [19]. In conjunction with RTCA, a standard for DAA systems was released in 2017, DO-365 [46]. It uses a τ_{mod} value of 35 seconds with a distance threshold (both a minimum distance (or, distance modification - DMOD) and horizontal miss distance filter) of 4000 feet in the horizontal plane. The vertical component of the Well Clear definition was determined by either a distance from ownship UAS of 450 feet or a time-to-co-altitude value of 20 seconds. This recommendation was not adequate for small UAS and VLL operations. Hence some scaling of the parameters was done. In addition, a Well Clear boundary of 2200 feet laterally and 450 feet vertically is proposed for non-cooperative encounters. The selection was based on findings in [47], [48] and published in later review of DO-365B [49]. Note that the terms of reference and scope of the standard currently does not include sUAS-sUAS encounters.

A more recent recommendation is defined by MIT LL, considering small UAS in VLL operations [13]. In distinction from the first RTCA DO-365 MOPS recommendation, it uses only spatial metrics, using a “hockey-pock-shaped” volume

with a distance threshold (both a minimum distance (or, distance modification - DMOD) and horizontal miss distance filter) of 2000 feet in the horizontal plane. The vertical Well Clear component is determined by a fixed distance from the ownship sUAS of 250 ft. These metrics were adapted and published as part of American Society for Testing and Materials (ASTM) Standard Specification for Detect and Avoid System Performance Requirements (ASTM F38) [3]. It is worth mentioning, ASTM F38 DAA performance standard is only applicable to avoidance of manned aircraft by sUAS and not sUAS to sUAS.

B. SELF-SEPARATION BASED ON sUAS PERFORMANCE

Michael. M. et. al. [18] proposed a time-based separation method, applicable for small UAS operations. Using worst-case analysis regarding UAS maneuverability and ground speed range, they show how to generate dynamic separation thresholds. However since their time metrics were based on the recommendations of Second Caucus Workshop (i.e. suitable for large UAS and UAS-manned aviation encounters), the values resulted way too large to be considered adequate for sUAS operations.

In this work [50], the authors focus on sUAS operations in urban environment. They propose a preliminary WC volume with radius of 20 ft and half-height of 24 ft. Given the low sUAS speeds and high maneuverability (i.e. high turning rate), they demonstrated that safety might be acquired with much less conservative thresholds. The authors argue that these parameters are proposed due to sUA small size and the capability to do turn maneuvers with 30 degrees per second. Nevertheless, no explicit methodology is given in how to define well clear for sUAS.

McLain. et.al [14] analyzed high density sUAS operations and proposed a methodology to define well clear based on the limitations of an ADS-B dependant airspace and sUA maneuver capabilities. The authors calculate spatio-temporal self-separation thresholds by determining minimum distance and time between an intruder and maneuvering sUAS. Similar to Michael. M. et. al. [18] this separation minima depend on horizontal maneuver capability in stressing head-on encounters. The standard definitions recommended by SARP are analyzed to demonstrate their method. Results showed that the recommendations were too conservative for sUAS operations and recommend for horizontal WC definition to be 3200 ft distance or a modified tau (τ_{mod}) of 25 seconds.

Considering a service oriented airspace (i.e. UTM/U-space), this work [51] successfully simulates safe sUAS delivery missions. Each sUAS is subscribed to CD&R services which help the vehicles to keep a self-separation distance. The authors recommend horizontal thresholds varying from 30 to 45 meters based on Total System Error of the sUAS and an arbitrary safe separation minimum.

There is no (up to date) definitive well clear concept or another alternative approach recommended from U-Space. Nevertheless, CORUS as part of the initial projects, proposes some minimal distances to be considered at

VLL operations [52]. In the case of beyond visual line of sight encounters (BVSOL) between two sUAS, a horizontal distance of 250 ft and 150 ft vertical, is considered as separation minima. To the best of our knowledge no explanations whatsoever are provided to the open public regarding the methodology.

C. LIMITATIONS AND GAPS ON sUAS WELL CLEAR STANDARD

To give a comprehensible overview on Well Clear standard for sUAS, we extracted the main processes (i.e. activities) — which refers to the method of choice, model assumptions, simulation and experimental set-ups — that each work in literature review has considered to define WC (see Table 1). The authors recognize all activities as complementary elements that need to be taken into account, and do not compare the weight of their importance.

As evidenced, a lot of work has been done related to safety of UAS and recently small UAS. Section III.A summarizes works that base their contributions on principles 1,3,4,8 and partially 2 (since unmitigated collision risk analysis does not require any type of DAA systems). While this approach has been proved to have significant contributions on the standardization process of Well Clear for medium to large UAS, it is difficult to be adapted and define adequate self separation metrics for sUAS operations. One main concern that the authors have, relies on the compatibility with the DAA systems. In our understanding, the DAA system role is far more important in sUAS environments, than in case of large UAS or manned aviation due to access of Separation Provision Services (see section II.B). Furthermore, this approach requires static separation thresholds, which has negative impacts on the airspace capacity.

In our opinion, the primary contribution of the Section III.A lies on the identification of the encounter geometries between sUAS, rather than in direct quantification of self-separation thresholds. It is worth mentioning that none of the reviewed works, considered sUAS-sUAS encounters while attempting to define WC criteria.

Section III.B, summarizes the works that follow principles 2,3,4,5,7,9 and 10. Since this approach is mainly based on the sUAS performance, typically *Scripted Encounters* are used to create stressing situations (e.g. head-on) and evaluate the performance of each system. This might be one of the trade-offs that this method has to consider, which can be remedied by the work derived from Section III.A. In addition, it was observed that the quite often authors quantify the criteria based on expert's experience [50], [51], [53] and/or deriving from manned aviation standards (e.g. TCAS metrics) [14], [18]. While we do agree that *scaling factor* presumptions can be used to evaluate DAA systems and methods, it appears not to be very rigorous when it comes on determining Well Clear.

Given this picture of sUAS Well Clear separation standard, the authors attempt to overcome the limitations mentioned above, by formally justifying their assumptions and utilizing fast simulations to verify and give the most adequate

TABLE 1. sUAS WC processes.

Extracted processes from Literature Review	Nr.
Unmitigated Collision Risk Method and analysis	1
sUAS (aircraft and systems) performance behavior	2
Fast simulations / Monte Carlo	3
Operational Acceptability	4
Simulations in the Loop / Hardware in the loop	5
Real Flight Tests	6
Scripted Encounters (head-on, crossing...)	7
Representative sUAS trajectories	8
sUAS-sUAS encounters	9
Environmental Uncertainties (e.g. wind)	10

recommendations based on severity of loss of separation and operational considerations.

D. ALTERNATIVE DAA SYSTEMS

Aircraft Collision Avoidance System X (ACAS-X) [54] is projected to play a key role in the safety of the Next-Generation Air Transportation System (NextGen) and replace the currently deployed TCAS-II [20]. Based on this concept a new version ACAS-Xu [55] has been developed to provide DAA capabilities to UAS. It meets the functional requirements proposed defined by MOPS and provides alert and guidance logic. Recent research has extended ACAS-Xu into ACAS-sXu, which takes into consideration the challenges raised by sUAS operations [56]. Based on similar approach systems like JADEM [57], SAFIT [50], and CPDS [58] are used to evaluate and test DAA systems that comply with the recommended MOPS.

E. EFFECTS OF EXTERNAL PARAMETERS ON DAA SYSTEMS

The effects of a number of factors and parameters have been evaluated to understand the influence they have on ensuring safe separation. Lee et. al. [59], provide two analyses regarding effects of the well clear threshold. Firstly, they give a study in dependencies of well clear metrics on the rate well clear violation occurrence. Secondly, a relationship between ATC separation and well clear volume definition. As part of a work from NASA Ames Research Center [40], a detailed evaluation of alerting logic and pilot response delay is shown. Three main parameters of DAA systems were checked as independent variables: trajectory prediction, alerting time threshold, and alerting distance threshold. Results indicated DAA alerting distance has a greater effect on DAA system performance than alerting time or ownship trajectory prediction.

Consiglio et. al. [9], investigate different performance parameters such as a variety of well clear volumes, initial conditions, and encounter geometries. Kim et. al. [60], suggest a methodology to assess the conflict risk of sUAS traffic. It is shown that conflict risk is affected by the flow rate, the speed of sUAS, the intersection angle, and the number of sUAS. More research investigating other attributes of DAA systems such as Speed Range [61], [62], Turn Performance [62], [63],

Limited Surveillance Volume [64] has been done, giving different aspects and propositions that would be of interest for RTCA, ICAO, and other interested organizations.

IV. METHODOLOGY

In this section we define analytically and describe the separation method. Next, we show how to align this approach with Well Clear separation standard, by quantitatively defining a Well Clear boundary and its associated functions (e.g. Well Clear Recovery). Finally, we show the process and constrains on how to generate self-separation minima and alerting thresholds applicable for sUAS-sUAS encounters.

A. SEPARATION METHOD

This paper proposes a generic methodology to quantify well clear (self-separation) based on both the unmanned aircraft and systems performance, since we think it is an adequate alternative to help the integration of sUAS in low altitude airspace. Justifications why we choose this method are elaborated in detail in the paper. Given the fact that to define a WC volume two separate studies are required, and since the application of the methodology is similar for both the horizontal and vertical criteria, in this work we choose to focus only on one of the two criteria. In particular, we focus on the horizontal criteria, which are preferred in sUAS operations since: (a) Horizontal conflict resolution maneuvers are more preferable and a two dimensional approach is a common assumption in CD&R works [65]; (b) sensor accuracy is higher in horizontal dimension and performance of UAS is affected by flight level; (c) sUAS operate mostly in low altitudes, and flight-level regulations or constrains may cause sUAS to maintain flight level during their operations [66]. This might be to decrease the risk of collision with high buildings in urban areas. (d) It is also considered as conservative assumption; any method that operates adequately in two dimensions is likely to be able to perform adequately in three [67]. In any case, to the best of our understanding, two dimensional studies are useful and sufficient for preliminary investigations. In this study, we propose a separation method comprised in two layers of safety zones, as illustrated in Fig. 5. The inner layer is a fixed circle with radius R_{sNMAC} , modeled after the Near Mid Air Collision (NMAC) concept, also referred as small NMAC (sNMAC) when applied to sUAS [68]. The outer layer is characterized by dynamic thresholds, which serve for sUAS to maintain self-separation. Here after we will refer to this area as Dynamic Well Clear Area (DWA).

1) SMALL NMAC AREA

To determine R_{sNMAC} we follow the method proposed in [51], [69], which considers the size of the UAS and an estimation of the total system error (TSE):

$$R_{sNMAC} = 2 \times MSW + TSE \quad (2)$$

,where in this case Maximum Wing Span (MWS) is the diagonal distance of sUAS and Total System Error (TSE)

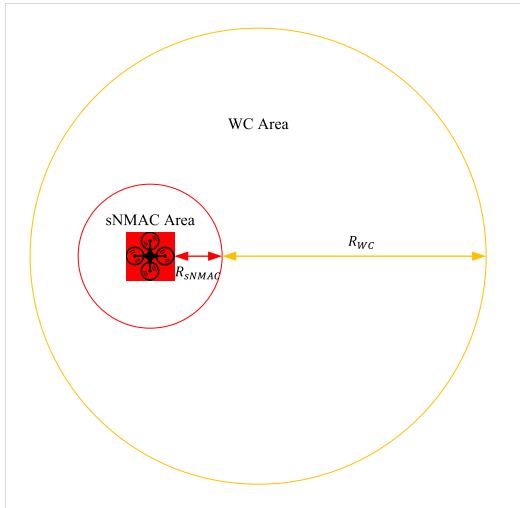


FIGURE 5. Well Clear and small NMAC area.

is composed of: Navigation System Error, Flight Technical Error, and Path Definition Error. For a more comprehensive discussion of TSE and its applications on small UAS, we suggest these papers [70], [71]. The sNMAC threshold is used to evaluate WC thresholds such that, WC threshold should be larger than sNMAC by an appropriate value that would prevent sUAS traffic getting to an unacceptable proximity (i.e. sNMAC cannot be evaded). In this work, we model a sUAS according to the characteristics of DJI Inspire 2 Quadcopter, which has $MWS = 0.6$ meters. To calculate TSE, we first need to assign the values per each component. Navigation System Error (NSE) is considered 2 meters, since it is the GPS standard accuracy. The values for Flight Technical Error and Path Deviation Error are obtained from [71], which under a normal distribution model for TSE, suggest a value of 3.58 meters. Therefore, an approximate value of $sNMAC = 4$ meters is used during our simulations.

2) DYNAMIC WELL CLEAR AREA

The Dynamic Well Clear Area is acquired from an early concept developed by US Air Force (USAF) [72], [73] and a later work adapted for sUAS [18], referred to as Dynamic Protection Zone (DPZ). It is defined by a circle representing the maximum reach set of the projected trajectory of the sUAS, as shown in Fig.5. Note that that the center of the circle has an offset distance from the UAS track position. The overall size of DWCA is adjusted based on the UAS heading and ground speed. The core idea behind this concept relies on the maximum range of maneuver that a sUAS can reach in a predefined time t . According to aforementioned papers, the heading change maneuvers can be grouped into three main modes: 1) sUAS turns at a turning rate until t is reached; 2) sUAS starts turning until a heading change θ , and then flies straight until t is reached; and 3) sUAS first flies straight and then turns at a given turning rate. Utilizing basic turning flight dynamics, it was shown that the maximum displacement from the original track, in a given time t ,

is achieved by the mode 2. This mode creates a kidney-bean like geometric boundary and the widest point is reached when the sUAS turns at maximum turning rate ω_m and spends as much as possible time at level flight approximately 1.6 radians (i.e. 90 degrees) with respect to the original track [18].

The relationship between the estimated positions and turning mode is given in 3. Lets assume that ownship sUAS has a constant ground speed V_o and a maximum turning rate (i.e yaw rate) ω_m , then the whole maneuver would consists of *turning* with ω for t_1 and *flying straight* with V_o for t_2 , where $t_1 + t_2 = t$. Supposing that sUAS is a point in a Cartesian reference frame with coordinates $O_1(0, 0)$, then in case of a maneuver, all possible positions of (x,y) can be expressed as:

$$\begin{cases} \theta = \omega t_1 \\ x = R \sin(\theta) + vt_2 \cos(\theta) \\ y = R + R \cos(\theta) + vt_2 \sin(\theta) \end{cases} \quad (3)$$

, where θ is the yaw angle (rad) (i.e. heading change with respect to original track), and R is the minimum *turning radius*, i.e. $R = \frac{V_o}{\omega_m}$. Note that, the original heading of sUAS is inline with x-axis and y represents lateral position of sUAS after t .

As mentioned above, all reaching points in mode 2, form an irregular boundary(i.e. kidney-bean) which would not be preferable as a separation standard. Therefore, a circle that encompasses this boundary is considered acceptable as separation boundary, without increasing its radius to sizes not acceptable for operational use. The radius of the circle is equivalent with the sum of maximum value of y and R_{sNMAC} as in 4:

$$R_t = R_{sNMAC} + V_o \times t_2 + \frac{V_o}{\omega_m} \quad (4)$$

, where $y_m = R + R \cos(\theta) + vt_2 \sin(\theta)$, $\theta = 1.6$ radians, and R is the minimum turning radius.

A visual description is given in Fig. 6, as it is shown in the right, the DWCA is modelled as a circle with radius R_t with center $O_2(0+l, 0)$, where l is an offset from origin $O_1(0, 0)$. The offset l can be expressed as $l = |x - x_m|$ and can be determined by simulations or analytically. In here, x is a random point and x_m is the maximum reaching point along x-axis, calculated under the same conditions as y_m , using equation 3. We give an analytical solution for the value of l , which serves as a constrain to determine R_t :

$$\begin{cases} R_t = y_m + R_{NMAC} \\ (x - x_m)^2 + y_m^2 \geq |V_o \times t - x| \end{cases} \quad (5)$$

In this paper, R_{WC} is considered as self-separation minimum, by which the WC area is determined(see Fig.5). This threshold is directly proportional to t , which in our approach is the total time that ownship sUAS requires to autonomously (i.e. no RP in the loop) maintain and/or regain Well Clear state. Note that R_{WC} is different from R_{WC} . The former describes a distance-based threshold, while the latter is a function, i.e. perform a maneuver to avoid a loss of WC from

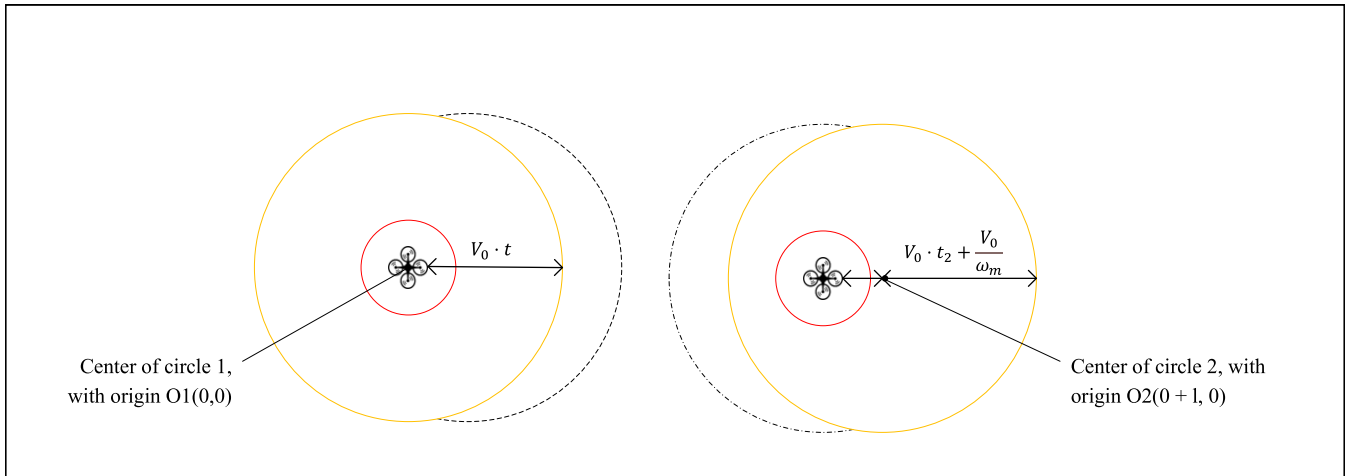


FIGURE 6. Non-maneuver reaching area (on left) and maneuvering reaching area (right).

occurring. We do not study RWC function in this work. The following subsection describes the evaluation of the separation minima.

B. SEPARATION MINIMA

To quantify R_{WC} , we have to determine t . We compute adequate values of t by considering it as sum of t_1 , the time a sUAS needs to alter its heading by 90 degrees with respect to its original track; t_2 which is the time the sUAS flies straight at level flight after altering its heading; and t_{TRT} which is the time of the system’s total response time (i.e. the time between the moment of conflict detection to the moment the execution of a conflict free maneuver begins)

$$t = t_1 + t_2 + t_{TRT} \tag{6}$$

In our approach t_{TRT} is considered an added safety buffer, to compensate the time lag of an on-board DAA system. It is composed of t_{sens} , the time the ownship needs to estimate the intruder’s state (also referred to as sensors update rate); t_{DAA} , the time the DAA method needs to detect a loss of WC, generate a conflict-free trajectory and send a command to the autopilot; and the autopilot response time t_{ap} , that is the time lag the on-board system requires to generate the right parameters to execute the maneuver received from DAA:

$$t_{TRT} = t_{sens} + t_{DAA} + t_{ap} \tag{7}$$

Furthermore, in this study we focus on specifying warning alert time-thresholds t_{al} , required for as a time-threshold that would prevent an intruder sUAS to enter ownship’s WCA by generating recovery maneuvers in case that loss of separation is unavoidable. We determine its value by using fast simulations and considering the following constraint:

$$T > t_{al} \geq t \tag{8}$$

V. EXPERIMENTAL SETUP

The experiments aimed to determine proper time values for t , which will be translated to spatial WC thresholds and

serve as adequate separation minimum. To attain this, we generate sUAS-sUAS encounters such that they would result is a loss of WC, t -seconds after the run of simulation, unless an avoidance maneuver is initiated. The analysis are focused on the severity of loss of WC results and WCR maneuver performance. For this purpose two metrics are introduced and an analysis method that can be used to derive proper recommendations.

A. SIMULATION ENVIRONMENT

In this work, we utilize Independent Configurable Architecture for Reliable Operations of Unmanned Systems (ICAROUS)⁵ as the simulation environment. ICAROUS is a software architecture that is designed for building autonomous unmanned aircraft applications. It is made of several core modules that include formally verified algorithms for detection, monitoring control of safety criteria. Furthermore, it comes with algorithms that avoid stationary obstacles and other airspace users. These algorithms calculate resolution and recovery maneuvers which are executed by the autopilot. ICAROUS incorporates DAIDALUS as DAA method (see section II/E). For our purposes, we rely on Pycarous, which is a Python wrapper for the core ICAROUS modules written in C++. As such, Pycarous allows for faster than real time. closed-loop simulation i.e. including a DAA system to mitigate possible conflicts. Furthermore it allows the implementation of near-realistic operational environment by adding uncertainty in several factors. More specifically, the positions of ownship and intruder are uncertain according to a Gaussian distribution $\mathcal{N}(0, 2)$ (i.e. mean 0 and variance 2 meters, set according to GPS technology parameters). Regarding the sensors update rate, we have assumed that both sUAS are equipped with ADS-B like type of sensors. In the simulation environment, the sensors update rate is modelled as a communication delay. Based on the current development and recommendation a reliable ADS-B update rate is

⁵<https://github.com/nasa/icarous>

TABLE 2. Characteristics of DJI inspire 2 quadcopter.

Characteristics	Values
Dimensions	60.5 cm
Maximum gross take-off weight	4 kg
Maximum flight time/endurance	27 minutes
Maximum airspeed	26 m/s
Maximum altitude	2500 m ASL (Above Sea Level)
Maximum pitch	90 °/s
Maximum yaw	90 °/s
Maximum roll	90 °/s

considered between 1 and 2 Hz [74]. However, it is suggested that for sUAS operation under a UTM ecosystem, the update rate might be further increased as part of the requirements of DAA systems [75]. Therefore, in this study we model communication delay (i.e., vehicle-to-vehicle) as a triangular distribution with minimum 0s, most likely value 1s and maximum 2s. Finally, wind speed is modelled by a Weibull distribution with shape 3.2 and scale 2.2, while wind direction is modelled by a uniform distribution between $[0, 2\pi]$ [71], [76]. In order to get statistically meaningful results, we utilize Monte Carlo simulations with 400 simulations per scenario setting. One simulation corresponds to a random sample of each variable modelled by a probabilistic distribution.

B. ASSUMPTIONS

The ownship and intruder UAS are modelled as point-mass. The ownship has constant ground speed v , and turning rate ω . On the other hand, the intruder cannot make maneuvers to change its speed or heading (i.e. fly through encounters). The reason the authors do not consider a maneuvering intruder is to enforce a worst-case scenario that comprises not only the encounter geometry but systems behavior as well. Based on the ICAO. Annex 2 (Rules of Air) a head-on is considered a high-risk situation and both aircraft should diverge from the original flight track to the right until a safe separation minimum is achieved. However, in our assumptions of the worst-case scenario, the systems behavior is taken in consideration as well. In other words, despite that we assume vehicle to vehicle communication is available, not all the sUAS can do a conflict resolution maneuver (i.e., not equipped with a DAA system). Another practical situation is considered for non-conforming sUAS as described here in [77]. In this manuscript, we use DAIDALUS as DAA reference method, which uses a linear state-based approach to detect and resolve conflicts. The results of a state-based predictions are only valid for the time that the state of the involved sUAS does not change (i.e., it behaves linearly within the look-ahead time). In case of maneuvering intruders, the DAA performance would not be acceptable due to a relatively high number of false positives (predicted loss of separations that will not actually occur). However, this is not true for a cooperative ecosystem (i.e., continuous exchange of sUAS state space). If the sUAS intent information is available, state-based prediction performs better, and the false positives are filtered out [78]–[80]. The only remaining issue would be the

uncertainties in communication delays, which could effect the intent information. Our model does consider these delays for the definition of the Well Clear separation minima, which can be thought as an added safety buffer to the Well Clear area. Therefore, theoretically speaking, if we would consider a maneuvering intruder, we expect that the change on the results would be very likely insignificant compared to the current results.

The sUAS parameters are based on a DJI Inspire 2 Quadcopter.⁶ Its characteristics are summarized in Table 2. While our experiments are based on the DJI Inspire 2 characteristics, our model is generic and can be updated according to different parameters. For instance, if we would use a sUAS with lower performance like DJI MAVIC3,⁷ ground speed and turning rate parameters would be changing accordingly, and therefore the safe separation boundaries around the sUAS. An illustrative case scenario is given in the discussion section.

Weinert *et al.* [13] have pointed out that often the advertised maximum and/or cruise airspeed normally do not match with the real-life achievable sUAS airspeed. For this reason, we alternate both sUAS ground speeds, by limiting the closure rate, $\max(CR) \leq 35$ m/s. The time parameter values regarding the systems behavior (DAA, Autopilot and Sensors Update Rate) are based on literature review [76], [81], [82]. It is very common that for sUAS having onboard decision making, the processing time is neglected, since it is typically less than 1 second. However, given the fact we assume a worst-case modeling, $t_{DAA} + t_{ap}$ is considered as 1 second. Regarding the sensors update rate, we have assumed that both sUAS are equipped with ADS-B like type of sensors and take the maximum value of the triangular distribution (i.e. 2 seconds) as described in the section V.A. Furthermore, we suppose that while maneuvering the ownship, sUAS can perform a heading change with maximum turn rate $\omega_m \in [30^\circ/s, 45^\circ/s, 60^\circ/s, 90^\circ/s]$ and fly straight at level flight for at least 1 second, $\min(t_2) = 1$ s. Given the aforementioned assumptions, t will be only dependant on turning rate. The formal definition is given in 9. To determine an upper limit for t_2 a systematic evaluation was done based on the severity level. Preliminary results stated that a $t_2 > 3$ seconds has little or no effect on the system's behavior.

$$\begin{cases} t_{TRT} = \max(t_{sens}) + \max(t_{DAA} + t_{ap}) \\ f(t_1) = t_1 + t_2 + t_{TRT}, \end{cases} \quad (9)$$

where $t_{TRT} = 3$ s and $t_2 \in [1, 2, 3]$ s.

C. SCENARIO GENERATION

We define a scenario as a particular ownship-intruder scripted encounter. In order to create a comprehensive set of scenarios, we formalize a scenario configuration as a tuple $(V, \Omega, D, \alpha, t_{al})$, where V is speed, Ω is turning rate, D is the WC threshold and α is the encounter geometry. The

⁶<https://www.dji.com/nl/inspire-2>

⁷<https://www.dji.com/es/mavic-3/specs>

TABLE 3. sUAS encounter matrix.

Parameter Type	#	Values
Ownship ground speed	2	10 m/s, 20 m/s
Intruder ground speed	2	10 m/s, 15 m/s
Encounter geometry	3	Head-on, Crossing, Over-taking
Maximum turning rate	4	30°/s, 45°/s, 60°/s, 90°/s
Flying straight time t_2	3	1s, 2s, 3s
Look-ahead time T	1	10 s
Alerting time t_{al}	3	$t, t + 1, t + 2$

intruder is generated based on the particular configuration of the ownship. More specifically, the initial position of the intruder is calculated by the relative range and bearing to ownship, where those values are in turn calculated by the angle α and time to loss of WC, held always constant at 15 sec. The time to LoWC is set relatively small in order to induce situations that are more likely to require WC recovery maneuvers. Generally, to quantify safety in the context of aviation, conservative approaches are followed. In our case, following a conservative approach means analyzing the worst-case encounters during short-time windows (i.e., less than 15 seconds). Since no other geometry can be riskier than the head-on encounter, we base our analysis on that. Moreover, the short-time windows comply with the requirements on communication and surveillance systems. Similar approaches are followed in various research works [83]–[85], that are used to evaluate DAA methods, system requirements and separation thresholds.

A total of 216 scenarios are generated by combining sUAS and encounter parameters as documented in Table 3.

D. METRICS

Two metrics are analyzed in this study:

- 1) Maximum Severity of Loss of Well Clear [60]. This metric captures LoWC events and gives information about the proximity between the sUAS per each encounter. In this context, a score of 0 means aircraft remained WC and a score of 1 a mid-air collision has occurred. A low separation severity is preferred. Formally, it is expressed as:

$$S_{max} = \max\left(0, 1 - \frac{d_{WC} - d(t)}{d_{WC}}\right) \quad (10)$$

where, d_{WC} is the well clear minimum separation distance and $d(t)$ is the distance between the ownship and the intruder at time t . Low values of S_{max} indicate that sUAS DAA system is more successful in regaining WC and preventing NMAC situations.

- 2) Average time between the time of LoWC and WC recovery time, denoted as T_{-WC} . This metric is utilized for operational reasons, in which T_{-WC} shouldn't be too large, since a loss of WC represents a risky situation and sUAS has a limited time to regain WC. It is assumed that this time should be approximately less or equal to the maneuver time [86].

VI. RESULTS

In this section, Friedman's test [87] is conducted to analyze the impact of the parameters defining the WC threshold such as closure rate, encounter geometry and environment uncertainty (e.g. wind), on LoWC severity. We utilize an alpha level 0.05 to show that the results are statistically significant.

To concisely present the results, we provide bar plots showing the maximum mean values considering only critical scenario sets. In the next subsection, we explain what we consider critical scenarios and how they serve best to the scope of this paper. Moreover, each bar plot is associated with a error bar, to give better comprehension of the results. Focused analysis on the specific scenario sets is provided in subsections B to E. The authors base their discussion and recommendations on the outcomes of this analysis. Three data sets (<https://dx.doi.org/10.21227/0d10-nm73>) are provided for the reader corresponding to analysis found on this manuscript for generating same results or for further investigations.

A. DATA FILTERING: CRITICAL SCENARIOS

In this paper we follow a worst case analysis to quantify the Well Clear Area and determine adequate Warning Alert time-thresholds. Keeping this in mind, the preliminary results served as a filtering process, to select and further analyse scenarios that fit best to the scope of the paper. In this regard, the following analysis focus only on critical scenario sets. Critical scenario set are considered the scenarios in the experiment, complying with the following constrains: 1) high risk encounter, i.e. high value of mean severity; 2) Sensitive towards influencing factors, e.g. WC threshold, Warning Alert time. Based on these two conditions, we exempt from further analysis overtaking scenarios and focus more into head-on encounters. Few exceptions are done. For instance, while showing the effect of the encounter geometry, we give a comparison between head-on and crossing scenarios. Note that while in the overtaking scenario the maximum severity tends to have high values (Fig 7), it is more a matter of the self-separation method and experiment design, rather than a high risk situation. More specifically, overtaking cases have smaller WC threshold, $R_{WC} = R_t - l$, and lower airspeed for ownship sUAS. This creates a long tail-chase situations, no matter the variance of parameters. For this reason, it is not considered as good indicator for our recommendations. However, we use the insight from the preliminary results for the general conclusions and the future work.

B. EVALUATION OF MEAN SEVERITY

In this study, WC threshold and Alerting Logic objective is to prevent high risk situations, that might lead into a NMAC event. In this context, low mean severity values are preferred and any occurrence of NMAC would indicate a failure of our self-separation approach for sUAS-sUAS encounters. The simulation results demonstrated no such situations, verifying the model assumptions. The bar plot in Fig.8 illustrates the

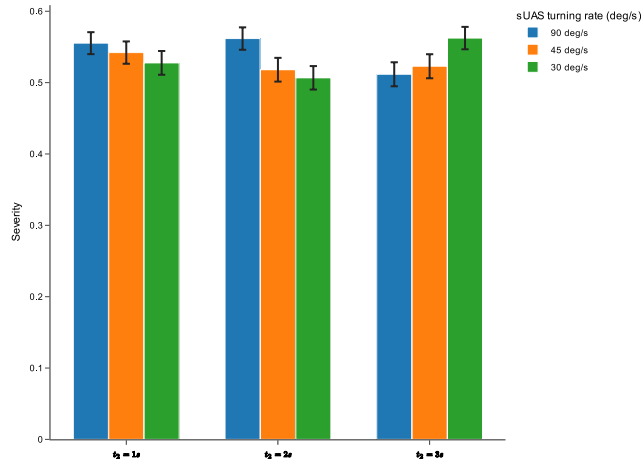


FIGURE 7. Mean Severity for Overtaking scenarios.

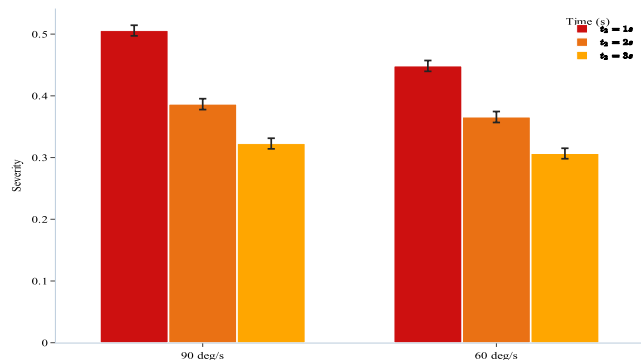


FIGURE 8. Mean Severity for high maneuverable sUAS.

average maximum severity for head-on encounters and high maneuvering sUAS. The categorization on the maneuverability is based on the data presented in [13]. The bar plots are grouped by the values of t_2 , where greater values imply larger WC threshold. In Fig.9, lower performance sUAS are shown. The lower values of severity compared to the previous plot, attributes to the fact that low performance sUAS have larger WC thresholds. The encounters with $t_2 = 1$ s, experience the highest average S_{max} . The minimum values of S_{max} , are obtained for $t_2 = 3$ s. Among the parameters included for the statistical analysis, it is observed that the results are statistically significant, with p-value, $p < 0.05$ and standard error, $SE < 0.02$.

It is worth noticing that higher performance sUAS and head-on encounters have higher difference in S_{max} values, thus are used in the next subsections to see the effects of the warning alert times, encounter geometry and closure rate on the maximum severity metric.

C. EVALUATING WARNING ALERT TIME-THRESHOLDS

In this subsection we attempt to analyze the effects of Warning Alert time-thresholds on the average severity behavior. In Fig.10, it can be seen that for larger Warning Alert time-thresholds, average S_{max} is lowered. For instance,

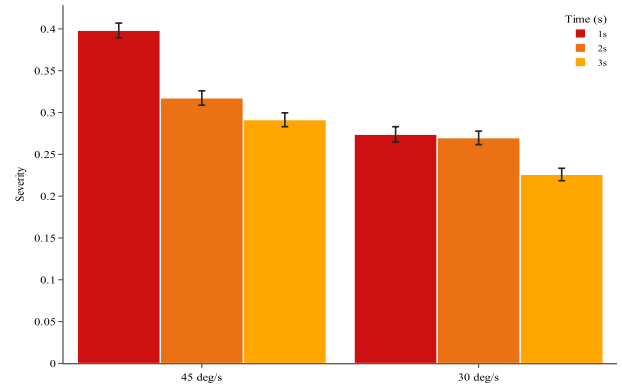


FIGURE 9. Mean Severity for low maneuverable sUAS.

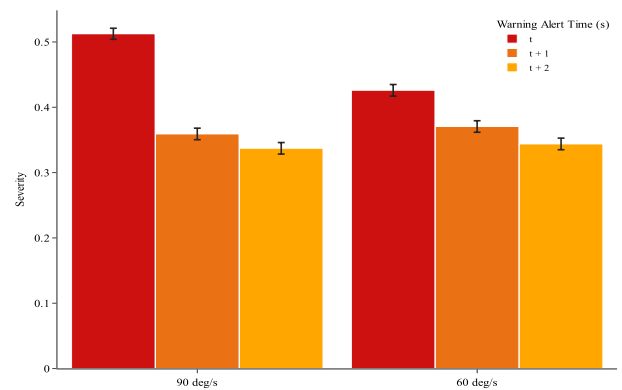


FIGURE 10. Mean Severity for different t_{al} values.

for $t_{al} = t = 5$ s (sUAS has a TR = 90 deg/s and $t_2 = 1$ s, the red bar shows the mean value $S_{max} = 0.51$ ($p < 0.05$, $SE < 0.01$); for $t_{al} = t + 1 = 6$ s, this value drops to 0.35 ($p < 0.05$, $SE < 0.01$); whereas for $t_{al} = t + 2 = 7$ s, mean value of $S_{max} = 0.24$ ($p < 0.05$, $SE < 0.01$). During result analysis was noted that the Warning Alert times reduces the severity significantly when we increase alerting time with 1 second. In the scenarios when alerting time is increased 2 s, the changes in severity are smaller and not that significant as for 1 second increment. This especially noticed in the encounters with lower turning rates.

In Fig.11, the performance of Warning Alert times on low maneuverable sUAS is shown. Since those sUAS have larger WC thresholds, they have lower severity and as such, the impact of warning alert times is even smaller. For the group with TR = 30 deg/s, increasing t_{al} with 2 seconds (yellow bar), has an insignificant change on severity compared to $t_{al} + 1$ seconds.

D. ENCOUNTER GEOMETRY, CLOSURE RATE AND UNCERTAINTIES

1) INFLUENCE OF ENCOUNTER GEOMETRY

To see the encounter geometry affects, the evaluation of mean severity was studied with respect to minimum and maximum WC threshold. In the Fig.12, mean S_{max} is shown for two combinations of the parameters. The first group shows a

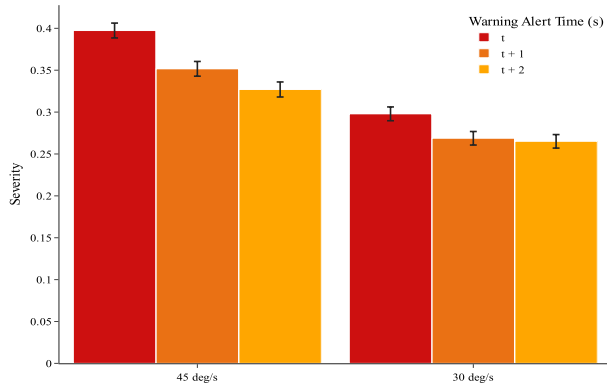


FIGURE 11. Mean Severity for different t_d values.

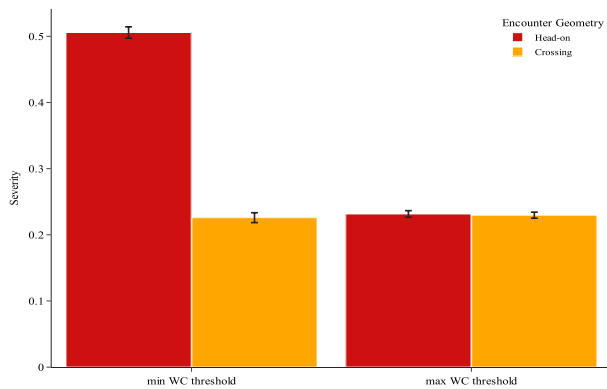


FIGURE 12. Influence of Encounter Geometry on Severity.

head-on scenario (the darker color) and crossing scenario (the lighter color) with respect to minimum WC threshold R_{WC} , i.e. $t = 5$ s. In the second group, the same parameters are computed with respect to maximum WC threshold, i.e. $t = 7$ s. The ground speed (GS) of sUAS and turning rate (TR) are kept constant, with ownship GS = 20 m/s, intruder GS = 15 m/s and TR = 90 deg/s.

We observe that for minimum WC threshold, the encounter geometry influences severity significantly; a value of $S_{max} = 0.5$ ($p < 0.05$, $SE < 0.01$) in head-on encounter is reduced to $S_{max} = 0.22$ ($p < 0.05$, $SE < 0.01$) for crossing geometry. In the other hand, for maximum WC threshold the difference can be considered neglectable with a difference in severity of 0.01. This is attributed to the fact that large WC thresholds create low risk situations, and are less sensitive toward different factors.

2) INFLUENCE OF SPEED

To understand the impact of the ownship sUAS speed and relative speed during the encounter. Since the WC area around the ownship depends on the sUAS performance, it results in smaller thresholds for lower performances. Due to this fact, sUAS with low speeds are expected to have higher severity. As it can be seen in Fig.13, S_{max} has peak values for encounters in which ownship has minimum speed (here, 10 m/s) and maximum intruder speed (here, 15 m/s). This is

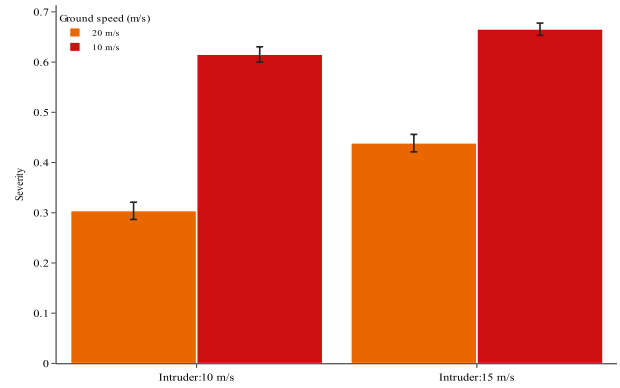


FIGURE 13. Influence of Speed on Severity.

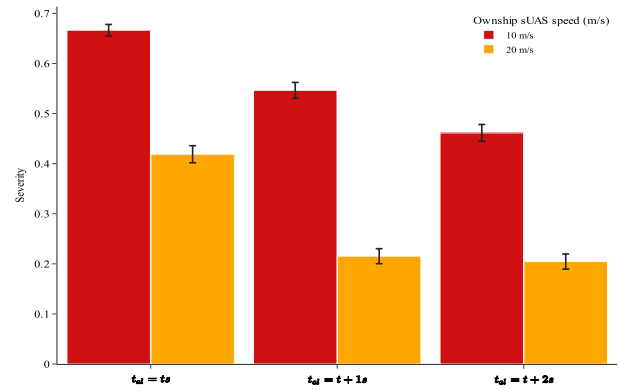


FIGURE 14. Influence of Speed on Severity for different t_d .

attributed to self-separation model, which does not take in consideration the intruder sUAS speed in an explicit way. In our approach we make use of the warning alert time-thresholds to reduce the risk in such scenarios. Fig. 14, illustrates that for intruders with maximum velocity (here, 15 m/s), larger warning alert time-thresholds reduce mean S_{max} value. It is worth noticing that low ownship sUAS speed has more impact on the severity, rather than high relative speed. For instance, in Fig.13, the case of ownship GS = 10 m/s and relative speed 20 m/s, has higher severity than when GS = 20 m/s and relative speed is 30 m/s.

3) INFLUENCE OF COMMUNICATION DELAY AND WIND

For this analysis, a critical scenario with minimum WC threshold ($t = 5$ s), head-on encounter, ownship GS = 10m/s and intruder GS = 15 m/s. The results are displayed in Fig.15. In the first run of simulation, both parameter values were assigned to 0, to create a deterministic scenario (light orange bar). The scenario was run only once, and S_{max} scored a value of 0.26 ($SE = 0$). Then in the environment we added communication uncertainty (see section V.A). In this case, 1000 runs were done and the red bar (delay) shows the severity value. Lastly the same procedure was done to evaluate the impact of wind. It is evident that the most influencing factor is the delay in communication system, with a value of $S_{max} = 0.73$ ($SE < 0.01$). This is attributed to the fact that

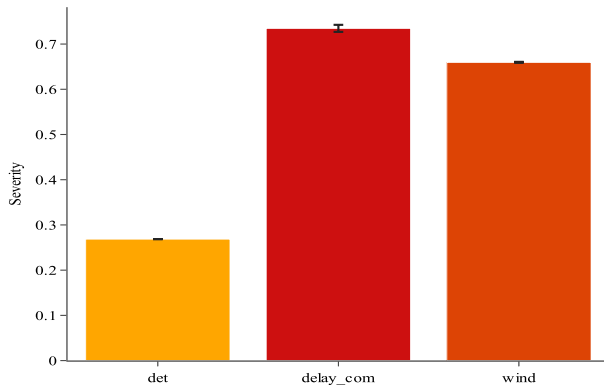


FIGURE 15. Influence of Comm. Delay and Wind on Severity.

DAIDALUS utilizes a deterministic model to project future states of sUAS. Therefore, it requires subsequent, in-time state information (e.g. position, speed), to accurately predict LoWC states and generate WCR maneuvers. Wind as well can influence severity $S_{max} = 0.65$ ($SE < 0.01$), but once the data about wind is provided to the DAA system, the state estimation can be done by considering airspeed instead of ground speed. Consequently reducing the error of prediction.

E. AVERAGE TIME BETWEEN LoWC AND WCR TIME

Figure 16 shows an overview of mean time that sUAS spend in LoWC or the time it was not well clear T_{-WC} , with the intruder sUAS. We illustrate different combination of turning rate and ground speed, to have a better insight on this value. We observed that for all the scenarios, T_{-WC} is less than minimum turning maneuver, indicating good initial assumptions for our model time input parameters. The maximum value, $T_{-WC} = 3.86$ seconds ($SE = 0.25$), is reached for low performance sUAS, such that $GS = 10$ m/s and $TR = 30$ deg/s. This is an expected result, given the fact that low performance sUAS need more time to perform a WCR maneuver.

VII. DISCUSSION

The findings of our study suggest that a sUAS performance based Well Clear standard can be safe and efficient for sUAS operations. The described methodology is a function of sUAS types, UTM capabilities and environmental uncertainties. To the best of our knowledge, the paradigm of sUAS ecosystems is different from the standard aviation and requires a system's thinking approach. In other words, we think that each component performance is directly measurable and can be quantified with statistical significance (comprising Aleatoric and Epistemic uncertainty). One may follow a worst-case analysis to model each composing system or develop a probabilistic model. The process underlies the same principles to determine a time threshold, which can be translated into spatial separation thresholds. These thresholds are dynamic with respect to the sUAS performance and environment, which contributes to a better management of airspace capacity.

In doing so, a better understanding of each system and their effects on the overall behavior can be studied. We think this is an important consideration, since there is a lack of "experience" in UAS operations and especially in case of sUAS. Therefore, a self-separation standard which is less dependent on expert assumptions or arbitrary choices (i.e. scaling factor see section III), can lead into compelling and complementary outcomes.

The results in VI.B. indicate no occurrence of NMAC and recovery of WC status in a timely manner. For sUAS with high maneuverability and in head-on encounters the mean severity is the highest for $t_2 = 1$ seconds ($S_{max} = 0.507$, $SE = 0.008$). In this scenario the method requires the minimum possible WCA, and further improvement can be considered. One solution, is to increase $t_2 = 3$ seconds, which would result in bigger WCA, and lower severity into ($S_{max} = 0.32$, $SE = 0.008$).

The results in VI.C show how the severity can be lowered by changing the Warning Alert Thresholds. For the same scenario described in the paragraph above, increasing alerting time with 1 second reduces mean severity from ($S_{max} = 0.507$, $SE = 0.008$) to ($S_{max} = 0.357$, $SE = 0.008$); and if alerting time is increased with 2 seconds, we have a better performance ($S_{max} = 0.337$, $SE = 0.008$). However as noted in the Results section, the change is not that significant. This might be attributed to the fact that we have a constant sensor update rate during the encounter and DAA has no use of early situation awareness to provide a recovery maneuver. In our opinion, larger alerting time thresholds would be more robust in a Remain WC event.

The results in VI.D show the sensitivity of the severity with respect to encounter geometry, closure rate and uncertainties i.e. communication delay and wind. It was indicated that severity is effected highly from the encounter geometry and communication delay. Two main points can be inferred from this analysis. Firstly, if a self-separation performs well in a head-on scenario, it is highly likely to perform at least as good in crossing encounters, under the same conditions. Secondly, once the intent information is available in encountering scenarios, communication delays have dominant effects on safe separation assurance.

VIII. RECOMMENDATIONS

In this section, we give recommendations related to adequate WC thresholds and Warning Alert Times. In subsection VIII.A we explain the reasoning behind our recommendations and give numerical values to quantify WCA and Warning Alert Threshold. Furthermore, in section VIII.B a hypothetical use case is given to illustrate how these recommendations can be used in a practical way.

A. WELL CLEAR AREA AND WARNING ALERT THRESHOLDS

The focus of this study is in airborne safety and the use of Well Clear standard to assure safe separation among sUAS

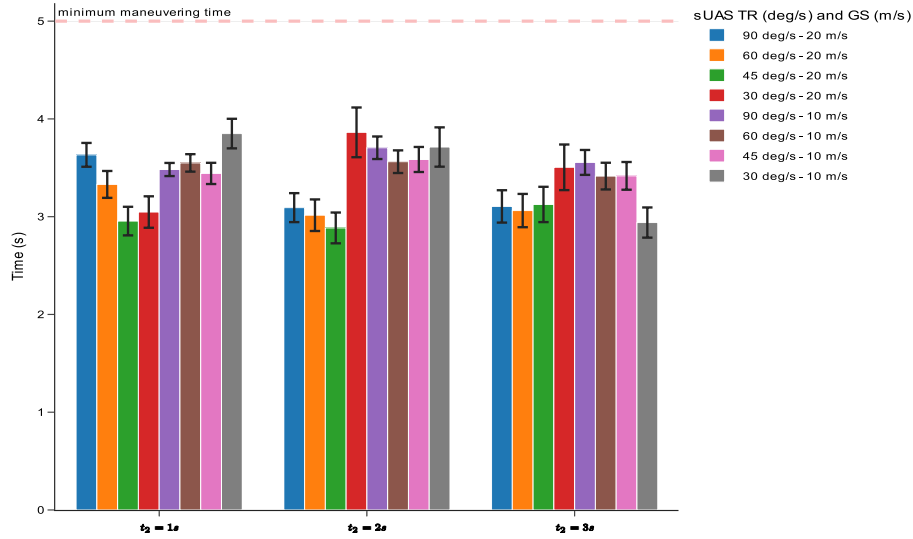


FIGURE 16. Average time in LoWC.

TABLE 4. Recommendations for high maneuverable sUAS.

	WC threshold (m)		Warning Alert Time (s)	
	Fast Intruder sUAS	Slow Intruder sUAS	Fast Intruder sUAS	Slow Intruder sUAS
Fast ownship sUAS	155	115	8	7
Slow ownship sUAS	70	60	8	7

TABLE 5. Recommendations for low maneuverable sUAS.

	WC threshold (m)		Warning Alert Time (s)	
	Fast Intruder sUAS	Slow Intruder sUAS	Fast Intruder sUAS	Slow Intruder sUAS
Fast ownship sUAS	165	145	8	8
Slow ownship sUAS	85	75	9	8

encounters. Final recommendations based on this study consider the following principles:

- Group the sUAS based on their ground speed and maneuverability similar to [88]. We group sUAS into *high-maneuverable sUAS* when their turning rate is greater or equal to 60 deg/s and *fast sUAS* when their ground speed greater or equal to 15 m/s. The rest is considered as *slow sUAS* and *low maneuverable sUAS*.
- Select combination of parameters (i.e. t_1 and t_2 that have the lowest severity).
- Evaluate operation suitability, (i.e. average time between LoWC and WCR time should be less than 5 seconds)
- Approximate the value to be multiple of 5, as it is common for use in aviation standards [68]

In Table 4 recommendations for *high-maneuverable sUAS* are shown. The data corresponds to sUAS with turning rate 60 deg/s and severity level less than 0.5. Note that, for sUAS with 90 deg/s the threshold can be smaller, while keeping the same value of severity. However, to avoid other unforeseen uncertainties in the systems, and considering that a WC maneuver tends not to be as sharp as a CA maneuver, a 60 deg/s maneuver is the best fit.

In the table 5 we present recommendation values for low maneuverable sUAS. We follow the same previous reasoning, and extract the data from sUAS with 30 deg/s turning rate. These criteria are compatible for sUAS with a turning rate up to 45 deg/s as shown by the results(section VI.B).

Regarding Warning Alert time-thresholds, based on the results analysis, it was observed that an alert value $t_{al} = t + 1$ s is the suitable case, considering that larger thresholds can cause false positive alerts and effect the performance [64]. The only exception in our recommendations, was the case of slow ownship and fast intruder for low maneuverable sUAS. In-there, $t_{al} = t + 2$ s compensates the relatively shorter WC threshold (75 m), to maintain a low level of mean severity.

B. USE CASE SCENARIO

In this hypothetical scenario, we assume that a delivery company similar to Uber Eats [89], has received an order for delivery. The company has several sUAS types in their fleet and for this particular case, is going to use a DJI Phantom 4 Quadcopter. The characteristics of sUAS are shown in Table 6 and all the sUAS are equipped with a DAIDALUS like DAA system.

Remote pilot (RP) has access to an UTM like ecosystem and before he starts the mission, a flight plan, together with

TABLE 6. Characteristics of DJI phantom 4 quadcopter.

Characteristics	Values
Dimensions	30.5 cm
Maximum gross take-off weight	1.4 kg
Maximum flight time/endurance	27 minutes
Maximum airspeed	20 m/s
Maximum altitude	2500 m ASL (Above Sea Level)
Maximum pitch	45 °/s
Maximum yaw	45°/s
Maximum roll	45 °/s

DAA Well Clear parameters need to be uploaded. A simple process can be as following:

- Generate a flight plan for sUAS to autonomously go from point A to B.
- Specify sUAS nominal ground speed and flight level. In this case, we assume it is 10 m/s and 250 ft AGL as in [90]
- Specify sUAS nominal turning rate. In this case we assume 30 deg/s.
- Share the information with the UTM to establish an updated situation awareness.
- Define WCA and Warning Alert Thresholds.

Given the fact that Uber Eats ownship sUAS belongs to the category of *low-maneuverable* and *slow sUAS* the thresholds should be taken from Table 5. Based on the situational awareness of surrounding traffic the DAA system should select the thresholds corresponding to Fast Intruders or Slow Intruders. A conservative case would be assuming that all the time there are Fast Intruders. Therefore, the RP should update the parameters of the DAA system with a WCA of 85 meters and Warning Alert Time of 9 seconds. In this condition, the mission should proceed safely in an autonomous way. In case that there is a demand of airspace capacity, and the nominal speed of sUAS falls into the category of *slow sUAS*, less conservative thresholds might be used. For instance, 75 meters WCA and 8 seconds Warning Alert Time.

IX. CONCLUSION

This study evaluated the quantification of Well Clear and Warning Alert Times in an analytical manner, unique to sUAS-sUAS encounters, operating autonomously in VLL airspace. To address the lack of an adequate separation method for sUAS, we adopt and extend a time-based separation approach, that requires dynamic separation thresholds based on the sUAS performance. A worst-case analysis was followed to determine the maneuver and system response time, which is used as input parameter t , to compute distance-based WC thresholds. Given that t is dependent of sUAS performance behavior, it generates dynamic thresholds, i.e. high performance sUAS require smaller WC thresholds.

The results of this work suggest that a WCA definition should include spatial WCA between 70 meters and 165 meters, and Warning Alert Time between 7 seconds and 9 seconds. These recommended thresholds were based on closed-loop fast simulations, by considering different aspects that might effect safety of the encounter such as: Encounter

Geometry and uncertainties in Communication Navigation and Surveillance (CNS) systems. A post-processing analysis of the results was done to derive best recommendations, by taking in consideration the maximum Severity of LoWC and average time between the time of LoWC and WC recovery time. The highest value of severity recorded was 0.51, indicating that there were no NMAC events and that sUAS recovered the WC status in a timely manner.

Overall, this study represents a systems thinking approach to pave the way for the quantification of a separation minima and criteria among sUAS which is an important gap for the future deployment of sUAS civil applications.

Validation of our results, through software and hardware in the loop simulations are next steps of this work. In addition, a complementary study should be done to address Remain WC and CA thresholds. There is also a need for testing the scalability and efficiency of the method, based on improved DAA systems. Furthermore, the investigation of a new scoring method, that would involve severity, T_{-WC} (time in LoWC) and impact in capacity management, should be considered.

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