# Introduction

Commercial and civil applications of unmanned aircraft systems (UAS) are projected to have a significant growth in the global market [], with the European UAS industry, expected to exceed 10 billion euro annually by 2035 and over 15 billion euro by 2050 [] [] (note that these projections are pre-Covid-19 pandemic). Furthermore, considering the characteristics of the missions and application fields, it is expeditious that the most market value will be in operations of small UAS (sUAS) and at the very-low-level airspace (VLL). Such a growing trend will be accompanied by increased traffic density and new challenges mainly related to safety, reliability, and efficiency.

Focusing on safety, one main concern is the risk for potential conflicts between UAS, which can lead to mid-air collisions when the conflicts are not mitigated in time. Essentially, a *conflict* refers to a state where two or more UAS are at a distance less than a predetermined separation minimum. This event can also be specified as *loss of separation* (LoS). Methods and systems that are well established to evaluate and maintain safety in manned aviation have been adapted and extended to UAS. For example, in Europe, SESAR is leading efforts to develop U-space (UAS traffic management solution for Europe), a set of services that accommodate current and future traffic in all classes of airspace and all types of vehicles. It will also provide a suitable interface for interoperability with Air Traffic Management services [] []. Whereas in the USA, NASA is developing and implementing a UAS Traffic Management (UTM) system, making it possible for many UAS to fly at low altitudes and other airspace users []. Similar approaches are followed by other countries such as China and Japan, and private stakeholders such Airbus [], Google [], Amazon []. The frameworks mentioned above provide services for operating the airspace free of conflicts through Conflict Detection and Resolution (CD&R) and Collision Avoidance (CA) methods.In UTM, similar to Air Traffic Management (ATM), conflict mitigation functions are widely conducted in three levels: Strategic Level, Tactical Level, and Sense and Avoid (SAA)/Detect and Avoid (DAA). These concepts are elaborated further in the second section (as a footnote).

In this work, we will focus on tactical CD&R applicable for small UAS missions. Although progressive work is done in traffic management of UAS, the up-to-date separation metrics and criteria are not adequate for operations in VLL airspace and sUAS-sUAS encounters [] [] []. This comes as a consequence of heterogeneous small UAS types (i.e., multirotor, fixed-wing), their performance capabilities (i.e., size, maximum take-off weight, maximum airspeed), airspace structure, unreliability in Communication, Navigation, and Surveillance (CNS), etc. [] []. Therefore, to assess the issue of traffic safety of small UAS, in this paper, we attempt to give answers to the following research questions:

1. What safe-separation (conflict mitigation) models are more efficient and reliable ( i.e., the need for dynamic separation thresholds)?
2. What are the inter-dependencies of minimum criteria and uncertainties, given a reference CD&R method, airspace environment, and safe-separation model?
3. What minimum separation metrics and criteria can be applied for sUAS only encounters?

To answer these questions, we adopt a dynamic protection zone as a separation model, based on the work in [ref][ref], and use it to specify minimal pairwise separation criteria at the tactical level between sUAS. The extended proposed model considers 1) Multirotor type sUAS; 2) The response time of the detection and resolution logic; 3) Delay in communication (i.e., both sUAS use ADS-B-like type sensors) and 4) Influence of uncertainties coming from GNSS navigation and wind.

To evaluate the proposed metrics and criteria, we utilized ICAROUS, an open-source (<https://github.com/nasa/icarous>) distributed software enabling safe autonomous operations of UAS. We consider pairwise scenarios operating in low-altitude, uncontrolled airspace and assume that one of the sUAS is equipped with a DAA reference system, addressed as the *ownship* sUAS. A synthetic *intruder* is injected by varying bearing, ranging, and heading, always resulting LoS, following the Closest Point of Approach (CPA) strategy [ref]. Herein, “intruder” is referred to as sUAS traffic, with no capabilities to maneuver.

Furthermore, due to inter-disciplinary research topics in UAS, we attempt to bring a comprehensive terminology, more clarity, and completeness to the subject of traffic management systems in sUAS. Therefore, this paper may facilitate research communities different from aeronautics such as engineering (i.e., telecommunications, software, systems) and social sciences (economics, law, management).

Overall, the main contribution of the work is estimation and recommendation of adequate separation minima and criteria that can be applied to tactical CD&R methods for sUAS only encounters by evaluating conflict severities under the influence of the effects in communication delay, encounter geometry, cruising airspeed, and uncertainties such wind and navigation errors.

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.

# Background

This section describes the current conflict management in manned aviation and introduces a framework concept of a UAS conflict mitigation system based on ICAO, NASA, FAA, U-Space, and other literature research. The analyzed UAS conflict management framework is considered an evolution of the present ATM system’s tactical and operational safety levels. Furthermore, we attempt to clarify the different terminologies leveraged from state of the art, such as Detect and Avoid (DAA), Sense and Avoid (SAA), Conflict Detection and Resolution (CD&R), Self-Separation, Well Clear, and so on.

## Traditional Air Traffic Management (ATM) system

The function of conflict management will be to limit, to an acceptable level, the risk of collision between aircraft and hazard (ICAO Doc9854/AN458) []. Conflict management, defined in ICAO and illustrated in Figure 1, consists of Strategic conflict management and Tactical Conflict Management(e.g., separation provision, collision avoidance). 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 latter is responsible for mitigating midterm conflicts (tactical) through gentle maneuvers in a timely fashion, also known as the separation provision function. In case that separation provision is compromised, Collision Avoidance (CA) is activated, presenting the operational level 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* (ATC-o). Note that the performance correlates strongly to human workload at this level and does not scale well in complex scenarios. In the event of an emerging collision, *Collision Avoidance System* (CAS) is enabled seconds before CPA. TCAS II and ACAS II are standard CAS systems mandatory for most commercial aircraft, and their main objective is pairwise collision avoidance. 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 [icao].

## UAS traffic management

Essentially, UAS traffic management follows similar safety layers as ATM: strategic conflict management, separation provision (or separation assurance), and collision avoidance. Note that UTM is responsible for mitigating conflicts caused by different types of hazards/risks such as *no-fly zones (i.e., airport areas), manned aircraft, terrain, and static obstacles.* In addition, we demonstrate a 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 U-Space/NASA-UTM concepts and spans four stages that asses all the safety layers mentioned above. First, to describe the framework, we follow a similar approach to this technical report for “dummies”[UUTM], which gives a simple explanation in an end-to-end process, covering all the stages of conflict mitigation applicable in sUAS operations. Next, we extend the tactical safety layer by introducing actual metric values, the verification of which lies in the scope of this work. Finally, we interpret plainly the functions related to conflict separation management and map them to the respective safety stages (layers).

### sUAS conflict management framework

The proposed framework comprises four stages, referred to as Strategic Conflict Mitigation (In some works, ICAO including, *conflict mitigation* syntax alternates with *Deconfliction*, we will keep using Mitigation to maintain consistency in this work, even though main concepts derive from ICAO proposals), Separation Provision, Self-Separation, and Collision Avoidance.

Stage 1 - Strategic Conflict Mitigation: here, conflicts are typically\* 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 (i.e., airports), weather, and other obstacles.

Stage 2 – Separation Provision: 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 anymore. The sUAS subscribed to this service 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: Derived from the *Airborne Separation Assurance Systems concept [],* it relies on the sUAS capabilities to maintain safe separation from other airspace users. This functionality can be carried manually by the remote pilot, 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: provides a final safety layer to prevent mid-air collisions. Typically is characterized by imminent and sharp maneuvers (or getting into a hovering state) and again can be managed by the remote pilot or autonomously.

The figure illustrates the general framework for managing sUAS conflicts.

The layered structure to manage conflicts use the concept of *preventive conflict mitigation,* which reduces the possible risk for mid-air collision while the intruder progresses through the layers. Here, stage 2 up to stage 4 deals with tactical conflict mitigation.

Stage 2 might be regarded as a cloud-based service enabled by the UTM ecosystem and requires seamless communication between sUAS and the service provider point (i.e., implemented as Amazon Web Services \*). In the case of a mid-air intruder that “escaped through stages 1 and 2, ownship sUAS uses Detect and Avoid capabilities to mitigate conflicts. Here, DAA spans both functions of stage 3 (self-separation) and stage 4 (collision avoidance) and can be remotely operated, assisted by a human in the loop, autonomous with the human on the loop, or fully automated[][].

DAA systems are necessary means for the safe integration of sUAS in civil airspace, grabbing a lot of attention in the research world, especially in the last decade.