# 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 the very-low-level airspace (VLL). Such a growing trend will be accompanied by an increase in traffic density and new challenges related to safety, reliability, efficiency, etc.

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 China and Japan, and private stakeholders such Airbus [], Google [], Amazon [], etc. 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 the 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. Synthetic traffic is injected by varying bearing, ranging, and heading, always resulting LoS, following the Closest Point of Approach (CPA) strategy [ref]. Hereafter the traffic will be referred to as the *intruder*, 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, etc.), social sciences (economics, law), etc.

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 tactical 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, strategical and tactical conflict management are 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, and collision avoidance. In addition, note that UTM is responsible for mitigating different types of hazards/risks such as *no-fly zones (terminal areas), manned aircraft, terrain, static obstacles, etc.* This paper demonstrates a sUAS conflict management framework (the framework is not necessarily limited to the small UAS) that deals only with airborne conflicts. It aligns with U-Space/UTM models and comprises four stages.

Phase I – Strategic conflict mitigation: