BUBBLES Separation Management Environment: architecture and validation of a separation management tool for UTM

BUBBLES 分离管理环境: 用于无人机交通管理 (UTM) 的分离管理工具架构与验证

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Abstract- With the growth of unmanned aviation, there has been an increased interest, or rather need, to define a framework or ecosystem that enables safe and efficient access to airspace for a large number of Unmanned Aircraft Systems (UAS), what is known as UAS Traffic Management (UTM). The development of UTM identifies services, roles, and responsibilities, as well as information exchanges between stakeholders. Among the challenges identified by the UTM, conflict management and separation provision stand out. In this context, BUBBLES, an Exploratory Research (ER) project funded by SESAR Joint Undertaking (SJU), defines a new concept of operations (ConOps) for the separation management service, a UTM service dealing with conflict management in tactical phase. The present paper outlines this ConOps, defines the architecture of a UTM tool developed to validate the BUBBLES concept, named Separation Management Environment (SME), and presents the validation exercise performed by means of test flights.

摘要 - 随着无人航空的发展，对于定义一个框架或生态系统以便大量无人机系统 (UAS) 安全高效地进入空域的兴趣或者说需求日益增加，这就是所谓的无人机交通管理 (UTM)。UTM 的发展确定了服务、角色和责任，以及利益相关者之间的信息交换。在 UTM 识别的挑战中，冲突管理和间隔规定尤为突出。在此背景下，由 SESAR 联合企业 (SJU) 资助的探索性研究 (ER) 项目 BUBBLES，为间隔管理服务定义了一种新的运行概念 (ConOps)，这是一种在战术阶段处理冲突管理的 UTM 服务。本文概述了这一 ConOps，定义了为验证 BUBBLES 概念而开发的 UTM 工具 Separation Management Environment(SME) 的架构，并介绍了通过试飞进行的验证练习。

Keywords—Separation management, U-space, UTM, separation minima, separation provision, BUBBLES, UAS (Unmanned Aircraft System), UAM.

关键词—间隔管理，U-空间，UTM，间隔最小值，间隔规定，BUBBLES，无人机系统 (UAS)，城市空中交通 (UAM)。

I. INTRODUCTION

I. 引言

In the last decade, the unmanned aircraft sector has attracted great interest due to its potential and numerous applications, especially in urban environments. This has led authorities and the general public to raise different issues and concerns, among which safety is one of the most relevant.

在过去的十年里，无人机领域因其潜力和众多应用而吸引了极大的兴趣，特别是在城市环境中。这导致当局和公众提出了不同的问题和关切，其中安全问题是最相关的之一。

Safety has been paramount in air traffic transport since the dawn of aviation. Conflict management is one of the main enablers of safety in aviation. According to [1], conflict management encompasses activities meant to limit, to an acceptable level, the risk of collision between aircraft and hazards, and is distributed in three layers: strategic conflict management, separation provision, and collision avoidance. Separation provision corresponds to the tactical layer of conflict management, which should be used when strategic conflict management is not enough to guarantee the required level of risk. Separation provision is hence the tactical process of keeping aircraft away from hazards by at least the appropriate separation minima [1] .

自航空诞生以来，安全一直是空中交通运输的首要任务。冲突管理是航空安全的主要促成因素之一。根据 [1]，冲突管理包括旨在将飞机与危险之间的碰撞风险限制在可接受水平的活动，并分布在三个层面: 战略冲突管理、分离规定和碰撞避免。分离规定对应于冲突管理的战术层面，当战略冲突管理不足以保证所需的风险水平时，应使用分离规定。因此，分离规定是通过至少保持适当的最小间隔，将飞机与危险隔离的战术过程 [1] 。

Conflict management in manned aviation is characterized by the intervention of human beings, the relatively low density of operations, and the centralized distribution of separation provision by ATC (Air Traffic Control) in controlled airspaces. However, the use of UAS presents a much different scenario, characterized by high levels of automation, a higher density of operations, and the distribution of service provision among several providers. Therefore, the direct application of traditional conflict management processes to UAS is not appropriate due to the differences between both scenarios.

有人驾驶航空中的冲突管理以人类的干预、相对较低的操作密度以及由空中交通管制 (ATC) 在受控空域中集中分配分离规定为特点。然而，使用无人机系统 (UAS) 呈现的是一个截然不同的场景，其特点是高度自动化、操作密度更高以及服务规定在多个提供者之间分配。因此，由于两种场景之间的差异，将传统的冲突管理过程直接应用于无人机系统是不恰当的。

Thus, the main contribution of BUBBLES project is to provide guidelines for dealing with UAS conflict management in the tactical phase, i.e., separation provision phase. For that, BUBBLES project proposes a UTM service, named Separation Management Service (SMS), whose objective is to provide airspace users with the information required to guarantee that the separation provision layer is performed homogeneously and according to specified criteria.

因此，BUBBLES 项目的主要贡献是为处理无人机系统在战术阶段，即分离规定阶段的冲突管理提供指导方针。为此，BUBBLES 项目提出了一个名为分离管理服务 (SMS) 的无人机交通管理系统 (UTM) 服务，其目标是向空域用户提供所需的信息，以确保分离规定层均匀且按照特定标准执行。

Moreover, in manned aviation, there is a set of separation minima defined according to standard procedures like those described in [2] and separation provision uses a few fixed separation minima for different scenarios. For instance, in [3], separations of2,2.5,3, and 5NM are used as reference separation minima to derive safety and performance requirements for generic surveillance sensors. Higher separations are used over oceanic or desert areas as they lack sufficient surveillance infrastructure. This is possible because manned aircraft have quite similar performances and fly rather simple trajectories. However, applying this approach to UAS operations, whose performance and mission types are more varied, leads to waste airspace capacity, as the airspace would have to be allocated considering that all aircraft are performing the operations that require the highest separation. Also, according to [1], as the environment and surveillance performance can change, separation minima can be dynamically adjusted to better suit the current status of the airspace. That is the reason why BUBBLES proposes dynamic separation minima, tailored to the traffic class, the operational environment, and the performance of the Communication and Surveillance (CS) systems.

此外，在有人的航空中，根据标准程序 (如 [2] 所述) 定义了一套分离最小值，分离规定为不同的场景使用几个固定的分离最小值。例如，在 [3] 中，将 2、2.5、3 和 5NM 作为参考分离最小值，用于推导通用监视传感器的安全性和性能要求。在海洋或沙漠区域，由于缺乏足够的监视基础设施，所以使用更高的分离值。这是可能的，因为有人驾驶飞机的性能相当相似，且飞行轨迹相对简单。然而，将这种方法应用于性能和任务类型更多样的无人机系统 (UAS) 操作，会导致空域容量浪费，因为空域必须考虑到所有飞机都在执行需要最大分离的操作。此外，根据 [1]，由于环境和监视性能可能会发生变化，分离最小值可以动态调整以更好地适应空域的当前状态。这就是为什么 BUBBLES 提出根据交通类别、操作环境和通信与监视 (CS) 系统的性能定制动态分离最小值。

In the context of BUBBLES, this paper presents a platform, named Separation Management Environment (SME), developed to validate the ConOps of the Separation management service. This platform allows to manage the separation between drones in real-time, providing them with the separation provision and making use of the dynamic separation minima given by the separation management service. The validation exercise consisted of test flights with 14 UAS flying simultaneously, in which UAS positioning data were sent to the SME platform, which detected any conflicts and provided the necessary alerts to the pilots to solve them. During that validation exercise, CS systems performance degradation was manually induced to simulate abnormal conditions. After the test flights, the performance of the SME platform was evaluated in terms of conflict detection and alert declaration, as well as the recalculation of dynamic separation minima according to the CS systems performance.

在 BUBBLES 的背景下，本文介绍了一个名为分离管理环境 (SME) 的平台，该平台用于验证分离管理服务的概念操作 (ConOps)。该平台能够实时管理无人机之间的分离，为它们提供分离保障，并利用分离管理服务给出的动态最小分离距离。验证练习包括 14 架无人机同时飞行的测试飞行，在此期间，无人机定位数据被发送到 SME 平台，该平台检测到任何冲突并向飞行员提供必要的警报以解决这些问题。在验证练习期间，人为引入了 CS 系统的性能降级，以模拟异常条件。测试飞行后，根据 CS 系统的性能，评估了 SME 平台在冲突检测和警报声明方面的性能，以及动态最小分离距离的重新计算。

The scope of BUBBLES concept covers UAS operating in the open, specific and certified categories defined in [4]; therefore, large RPAS flying under Instrumental Flight Rules (IFR) are not considered. The baseline for the development of this concept is the Concept of Operations (ConOps) developed by CORUS project [5].

BUBBLES 概念的范围涵盖了在开放、特定和认证类别下运行的无人机，这些类别在 [4] 中定义；因此，遵循仪表飞行规则 (IFR) 的大型 RPAS 不在考虑范围内。该概念开发的基础是 CORUS 项目 [5] 开发的操作概念 (ConOps)。

The present paper is organized as follows: section I sets up the framework where the concept is developed and justifies the need for such a concept; Section II outlines the ConOps for separation management proposed by BUBBLES project; Section III contains a detailed description of the SME platform; section IV details how this platform has been validated, including the description of the scenario, and the organization of the test flights; section V shows the results obtained from the validation exercise; and section VI contains the main conclusions.

本文的组织结构如下: 第一部分构建了概念发展的框架，并证明了此类概念的必要性；第二部分概述了 BUBBLES 项目提出的分离管理 ConOps；第三部分包含 SME 平台的详细描述；第四部分详细说明了如何验证该平台，包括场景描述和测试飞行的组织；第五部分展示了验证练习获得的结果；第六部分包含主要结论。

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[1] Separation minima are the minimum distances between an aircraft and a hazard that maintain the risk of collision at an acceptable level of safety.

分离最小值是飞机与危险之间的最小距离，这些距离将碰撞风险维持在可接受的安全水平。

II. SEPARATION MANAGEMENT CONCEPT

II. 分离管理概念

The separation management concept proposed by BUBBLES focuses on defining how the separation provision at tactical level must be implemented in UTM airspaces [2] so that all the conflicts arising therein are solved by applying the same rules and a particular Target Level of Safety (TLS) is achieved.

BUBBLES 提出的分离管理概念侧重于定义在 UTM 空域中战术层面的分离规定如何实施 [2]，以便所有由此产生的冲突通过应用相同的规则得到解决，并实现特定的目标安全水平 (TLS)。

Next, the separation provision process and the separation management service proposed by BUBBLES are explained.

接下来，将解释 BUBBLES 提出的分离规定过程和分离管理服务。

A. Separation provision process

A. 分离规定过程

As described before, conflict management is distributed in three layers: strategic conflict management, separation provision, and collision avoidance. The separation management is focused on the separation provision phase which, aims at limiting the risk of collision between aircraft and hazards to an agreed level deemed as acceptable by keeping aircraft away from hazards by at least the appropriate separation minima [1].

如前所述，冲突管理分布在三个层次: 战略冲突管理、分离规定和避撞。分离管理专注于分离规定阶段，该阶段旨在通过至少保持适当的分离最小值将飞机与危险保持距离，从而将飞机与危险之间的碰撞风险限制在商定的可接受水平 [1]。

Separation provision is an iterative process consisting of four steps [1]: (1) conflict detection, (2) solution formulation, (3) solution implementation, and (4) solution monitoring, as shown in Figure 1.

分离规定是一个迭代过程，包括四个步骤 [1]:(1) 冲突检测，(2) 解决方案制定，(3) 解决方案实施，以及 (4) 解决方案监控，如图 1 所示。

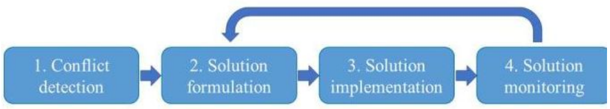

Figure 1. Separation provision process.

图 1. 分离规定过程。

The detection of a conflict is based on the latest known position of the involved aircraft and its predicted trajectory. In this first step, the definition of a conflict horizon, what a conflict is and how it can be detected should be defined. *A* conflict is defined as a predicted converging of aircraft in space and time which constitutes a violation of a given set of separation minima [6]. Therefore, conflict detection consists of predicting the expected distance at the closest point of approach (CPA) and the remaining time to the CPA within a given conflict horizon. A tactical conflict will be triggered if the distance at the CPA is less than the corresponding separation minima and the time to the CPA is lower than a pre-established threshold.

冲突的检测基于涉及的飞机的最新已知位置及其预测轨迹。在这一第一步中，应定义冲突范围、什么是冲突以及如何检测冲突。*A* 冲突被定义为飞机在空间和时间上的预测汇聚，这构成了对给定分离最小值集合的违反 [6]。因此，冲突检测包括预测在最近接近点 (CPA) 的预期距离和到 CPA 的剩余时间，在给定的冲突范围内。如果 CPA 的距离小于相应的分离最小值，并且到 CPA 的时间低于预先设定的阈值，则会触发战术冲突。

Solution formulation involves the identification of a separator, the definition of separation modes and the selection of separation minima and methods to be used. This step is related to the intervention capability, which is the capability of humans and/or systems to detect and solve a conflict and depends on the level of automation.

解决方案制定涉及识别分隔符、定义分离模式以及选择分离最小值和使用方法。这一步骤与干预能力相关，干预能力是指人类和/或系统检测和解决冲突的能力，它取决于自动化水平。

- The designation of a separator. According to [1], the separator is the agent responsible for separation provision when a conflict is detected and can be either the airspace user (a human being optionally supported by an electronic system or a fully autonomous system) or a separation provision service provider (named USSP in Europe).

- 分隔符的指定。根据 [1]，分隔符是在检测到冲突时负责提供分离保障的代理，可以是空域用户 (一个由电子系统支持的人类或完全自主系统) 或分离保障服务提供商 (在欧洲被称为 USSP)。

- The selection of a separation mode. The separation mode consists of an approved set of rules, procedures and conditions of application associated with separation minima and methods.

- 分离模式的选择。分离模式包括一套经批准的规则、程序和应用条件，与分离最小值和方法相关联。

- Separation minima are the distances aircraft must be kept away from the considered hazards so that an agreed TLS can be achieved. Separation minima do not necessarily consist of a fixed set of, values but can be dynamically determined from scenario-related parameters.

- 分离最小值是飞机必须与考虑到的危险保持的距离，以便实现商定的最小安全间隔 (TLS)。分离最小值不一定是一组固定值，而可以根据场景相关参数动态确定。

- Separation methods are specific maneuvers that need to be executed to maintain the separation minima.

- 分离方法是需要执行的具体机动，以保持分离最小值。

- Separation rules and conditions specify how the separator agent must apply the separation minima and methods.

- 分离规则和条件规定了分隔代理必须如何应用分离最小值和方法。

The solution implementation is a three-fold process: (1) notification of the solution defined in step 2 to the agent which serves the function of controlling the UAS (either the pilot in command or any on-board electronic flight control system); (2) the agent executes the maneuvers needed to avoid the hazard; and (3) the UAS performs the maneuvers executed by the agent in control. The way how the solution is implemented strongly depends on the automation level.

解决方案实施是一个三步骤过程:(1) 将第 2 步中定义的解决方案通知给负责控制无人机系统 (UAS) 的代理 (无论是机长还是任何机载电子飞行控制系统)；(2) 代理执行避免危险的所需机动；(3)UAS 执行控制代理的机动。解决方案的实施方式强烈依赖于自动化水平。

The monitoring of the execution of the solution. BUBBLES considers different agents in charge of monitoring the implementation of the formulated solution and warning the separator agent in case it is ineffective.

监控解决方案的执行。BUBBLES 考虑了不同的代理负责监控制定解决方案的实施，并在该解决方案无效的情况下警告分离代理。

Therefore, to properly conduct the separation provision process, the definition of what a tactical conflict is, as well as the applicable separation minima, are required. In addition, the applicable rules for solution formulation and implementation shall be clearly defined and published, so that all involved agents can follow the same set of rules. Finally, the responsibilities of the involved agents shall also be clearly defined. All this information must be covered by the separation management service, which is described next.

因此，为了正确执行分离规定过程，需要定义什么是战术冲突，以及适用的分离最小值。此外，解决方案制定和实施的应用规则应当明确界定并公布，以便所有相关代理都能遵循相同的规则集。最后，还应当明确界定相关代理的责任。所有这些信息都必须包含在分离管理服务中，如下所述。

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provided to UAS to guarantee safe operations. For simplicity, 'UTM airspace' term will be used in this paper.
提供给 UAS 以确保安全运行的。为简化起见，本文将使用“UTM 空域”这个术语。

[2] UTM airspace refers to a volume of airspace in which UAS operations take place regularly and a set of UTM services are

[2] UTM 空域指的是无人机系统定期进行操作的空域，并提供了一套 UTM 服务。

B. Separation Management service

B. 分离管理服务

To cope with separation management in UTM airspaces, BUBBLES project proposes to provide a new UTM service, called Separation Management Service (SMS), to all UAS flying therein. The objective of the SMS is to make available all the information required for UAS users to univocally define the separation mode, so that all tactical conflicts occurring within a given airspace are solved according to a pre-established set of rules and procedures, and a target effectiveness of the separation provision barrier is achieved so that a particular TLS can be attained.

为了应对 UTM 空域中的分离管理，BUBBLES 项目提议为所有在该空域内飞行的 UAS 提供一项新的 UTM 服务，称为分离管理服务 (SMS)。SMS 的目标是使 UAS 用户能够明确地定义分离模式所需的所有信息，以便在给定空域内发生的所有战术冲突都能按照预先设定的规则和程序解决，并且分离保障屏障的目标有效性得以实现，从而达成特定的 TLS。

The SMS is responsible for providing information on the conflict horizon, the separator agent, the separation mode, the separation method, the separation minima and the required SPR/HPR (Safety and Performance Requirements/Human Performance Requirements). To this purpose, the separation management concept is structured in 5 blocks, each of them charged with the responsibility of providing one particular piece of information so that the service can be provided by assembling them. Figure 2 shows the conceptual architecture of the BUBBLES separation management service, where the light blue boxes correspond to static information defined when designating a UTM airspace and the dark blue one stands for information which is dynamically updated at the operational level.

SMS 负责提供关于冲突范围、分离代理、分离模式、分离方法和分离最小值以及所需的 SPR/HPR(安全与性能要求/人类性能要求) 的信息。为此，分离管理概念被结构化为 5 个模块，每个模块负责提供特定信息，以便通过组合它们来提供服务。图 2 显示了 BUBBLES 分离管理服务的概念架构，其中浅蓝色框对应于在指定 UTM 空域时定义的静态信息，深蓝色框代表在操作层面动态更新的信息。

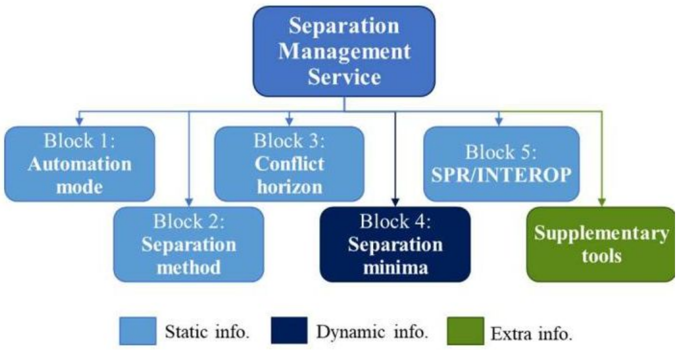


Figure 2. Conceptual architecture of the BUBBLES separation management service.

图 2. BUBBLES 分离管理服务的概念架构。

The first block is in charge of the definition of the available options regarding the level of automation to be used for tactical deconfliction processes. This block also defines the agents responsible to execute any of the four steps of tactical deconfliction (conflict detection, solution formulation, solution implementation, and monitorization of the solution), according to the level of automation.

第一个模块负责定义在战术冲突解决过程中可用的自动化水平选项。该模块还定义了负责执行战术冲突解决的四个步骤 (冲突检测、解决方案制定、解决方案实施以及解决方案监控) 的代理，这取决于自动化水平。

The second block is focused on the description of the possible maneuvers and/or actions that UAS operators and USSPs can use during the solution formulation step of the tactical deconfliction process.

第二个模块专注于描述在战术冲突解决过程中的解决方案制定步骤中，无人机系统操作员和无人机系统服务提供商 (USSP) 可能使用的机动和/或行动。

The third block defines the Conflict horizon [3] to be considered during the solution formulation step of the tactical deconfliction process. The conflict horizon defined by the separation management service is related to the probability that the proposed separation maneuvers will lead to additional conflicts with nearby aircraft.

第三个模块定义了在战术冲突解决过程中的解决方案制定步骤中需要考虑的冲突视界 [3] 。由分离管理服务定义的冲突视界与提议的分离机动导致与附近飞机产生额外冲突的可能性有关。

The fourth block consists of the publication of the applicable separation minima in the pre-operational and operational phases. In the operational phase, the separation minima are dynamic values that are updated in real-time depending on the CNS performance.

第四个模块包括在预操作和操作阶段发布适用的最小间隔。在操作阶段，最小间隔是动态值，根据通信、导航和监控 (CNS) 性能实时更新。

The fifth block consists of the publication of the SPR/INTEROP (Safety, Performance and Interoperability requirements) related to separation management that are required UAS operators and USSPs to operate in a UTM airspace.

第五个模块包括发布与分离管理相关的 SPR/INTEROP(安全、性能和互操作性要求)，这些要求是无人机系统操作员和无人机系统服务提供商在无人机交通管理系统 (UTM) 空域运行所必需的。

To produce all the information needed to support the solution of tactical conflicts, the SMS uses a set of supplementary tools, namely: reference scenarios, an Accident Incident Model (AIM), a study of TLS that must be attained; a tool to estimate the risk of the mid-air collisions (MAC), and a tool to compute the airspace capacity limit due to mitigated mid-air collision risk.

为了生成支持战术冲突解决所需的所有信息，分离管理服务 (SMS) 使用一套辅助工具，具体包括: 参考场景、事故事件模型 (AIM)、必须达到的空对空避撞系统 (TLS) 研究；一种估计空中相撞风险的工具，以及一种计算因降低空中相撞风险而受限的空域容量限制的工具。

To ensure the harmonization of the conflict management process among all involved stakeholders, the separation management service is required to be centrally provided, acting as the single point of truth from which all airspace users collect the data required to execute the separation provision phase.

为了确保所有相关利益相关者在冲突管理过程中的协调一致，分离管理服务需要集中提供，作为所有空域用户收集执行分离规定阶段所需数据的单一真实信息来源。

III. DESCRIPTION OF THE SEPARATION MANAGEMENT TOOL

III. 分离管理工具的描述

In order to validate the concept of the separation management service described above, we developed a U-space [4] platform, called BUBBLES Separation Management Environment (SME).

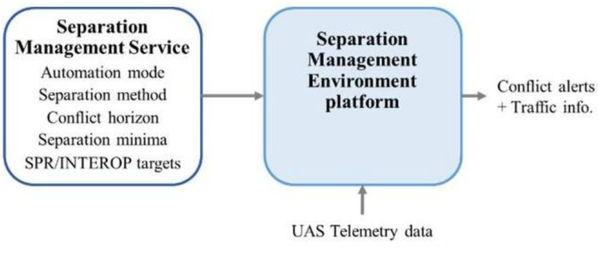
为了验证上述描述的分离管理服务的概念，我们开发了一个名为 BUBBLES 分离管理环境 (SME) 的 U-space [4] 平台。

The BUBBLES SME platform is an environment developed to monitor UAS in real-time by providing them with separation provision. As can be seen in Figure 3, this platform uses as input data the information given by the separation management service (as described above and in [7]) and the UAS telemetry data. This platform follows the steps of the separation provision process and detects potential conflicts and sends alerts to the pilots.

BUBBLES SME 平台是一个开发环境，用于通过为无人机系统 (UAS) 提供分离保障来实时监控它们。如图 3 所示，该平台使用分离管理服务提供的信息 (如上所述及在 [7] 中描述) 和 UAS 遥测数据作为输入数据。该平台遵循分离保障流程的步骤，检测潜在的冲突并向飞行员发送警报。

[3] The extent to which hazards along the future trajectory of an aircraft are considered for separation provision [1].

[3] 在为分离保障考虑飞机未来轨迹上的危险程度 [1]。



[4] U-space is the local implementation of the UTM concept in Europe. U-space and UTM terms can be used interchangeably throughout this paper.

[4] U-space 是在欧洲实施 UTM 概念的本地化版本。本文中 U-space 和 UTM 术语可以互换使用。

Figure 3. Inputs and outputs of the SME platform.

图 3. SME 平台的输入和输出。

This platform includes some pseudo-U-space/UTM services required for the good functioning of the test flights and to test the BUBBLES concept, such as tactical conflict resolution service, traffic information service or tracking service. This service is also aligned with the Conflict management and separation service defined by [8].

该平台包括一些伪 U-space/UTM 服务，这些服务对于测试飞行的良好运行和测试 BUBBLES 概念是必需的，例如战术冲突解决服务、交通信息服务或跟踪服务。此服务还与 [8] 定义的冲突管理和分离服务保持一致。

Figure 4 shows the high-level architecture of the SME platform.

图 4 显示了 SME 平台的高层架构。

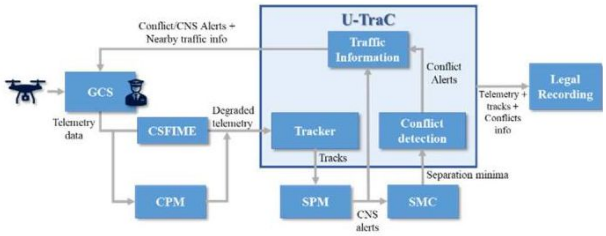


Figure 4. Architecture of SME platform.

图 4. SME 平台的架构。

At a high-level description, when operating, the SME platform:

在高层次描述中，当运行时，SME 平台:

1. Receives telemetry and registration information that the UAS Ground Control Station (GCS) transmits to the tracker.

1. 接收无人机地面控制站 (GCS) 传输给跟踪器的遥测和注册信息。

2. The Communication and Surveillance Fault Injector and Monitoring Environment (CSFIME) adds degradation to the telemetry data.

2. 通信和监视故障注入与监控环境 (CSFIME) 对遥测数据添加降级。

3. The tracker, built-in in the U-space tracking & Conflict detection (U-TraC) component, processes the received UAS degraded reports and generates drone tracks using tracking algorithms.

3. 跟踪器内置于 U 空间跟踪与冲突检测 (U-TraC) 组件中，处理接收到的无人机系统 (UAS) 降级报告，并使用跟踪算法生成无人机轨迹。

4. The Communication and Surveillance Performance Monitoring (CPM and SPM) components compute performance metrics to assess and evaluate the effects due to degradation on the communication and surveillance data. When degradation is detected, they send a message to the Separation Minima Calculation (SMC) component.

4. 通信与监视性能监测 (CPM 和 SPM) 组件计算性能指标，以评估和评估通信和监视数据降级造成的影响。当检测到降级时，它们向分离最小值计算 (SMC) 组件发送消息。

5. The SMC component computes the separation minima applicable to each aircraft according to the operational environment, the type of traffic, and the CNS performance status, applying AI algorithms.

5. SMC 组件根据操作环境、交通类型和通信、导航和监视 (CNS) 性能状态，计算适用于每架飞机的分离最小值，并应用人工智能算法。

6. The Conflict detection component detects conflict (up to 4 types of separation events as it is defined in the BUBBLES AIM [7]) computing the pairwise separation between UAS.

6. 冲突检测组件检测冲突 (如 BUBBLES AIM [7] 中定义的至多 4 种分离事件)，通过计算无人机之间的成对分离。

7. When a conflict is detected, it transmits an alarm/warning to the GCS through the Traffic Information component. The message includes the position of the conflicting UAS and a suggested maneuver in the vertical dimension to solve the conflict.

7. 当检测到冲突时，它通过交通信息组件向地面控制站 (GCS) 发送警报/警告。消息包括冲突无人机的位置和在垂直维度上解决冲突的建议机动。

8. During this process, telemetry data, tracks, conflicts, and information about the involved UAS are recorded for post-processing.

8. 在此过程中，记录遥测数据、轨迹、冲突以及有关涉及无人机的信息，以供后续处理。

Next, each of the components of the SME is described in more detail.
接下来，将更详细地描述 SME 的每个组件。

A. Ground Control Station (GCS)

A. 地面控制站 (GCS)

To connect the drones to the SME platform, an Android application based on the DJI Mobile Software Development Kit has been developed for the pilot controllers, named GCS in Figure 4.

为了将无人机连接到 SME 平台，已开发基于大疆移动软件开发工具包的 Android 应用程序，供飞行员控制器使用，如图 4 中的 GCS。

This application allows pilots to control the UAS while sending telemetry data, via 4G connection, to the SME and receiving conflict alerts, suggestive maneuvers, and other relevant traffic information such as nearby traffic or CNS status from the SME.

此应用程序允许飞行员在发送遥测数据至 SME 的同时，通过 4G 连接控制 UAS，并接收来自 SME 的冲突警报、建议机动以及其他相关交通信息，如附近交通或 CNS 状态。

Figure 5 shows the graphical interface of the pilot's commands app.

图 5 显示了飞行员命令应用程序的图形界面。

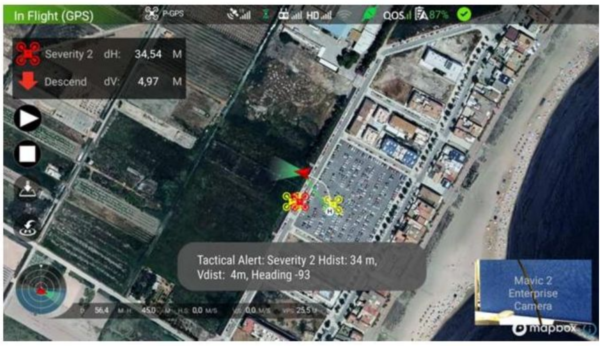


Figure 5. Pilots App interface.
图 5. 飞行员应用界面。

B. Communication and Surveillance Fault Injector and Monitoring Environment (CSFIME)

B. 通信与监控故障注入及监测环境 (CSFIME)

The CSFIME component adds degradation in the downlink to the telemetry data sent by the drone to the SME platform. The degradation includes GPS (Global Positioning System) position errors, latencies, and loss of packages.

CSFIME 组件在无人机发送到 SME 平台的下行链路中对遥测数据添加退化。这种退化包括 GPS(全球定位系统) 位置误差、延迟和数据包丢失。

The Pilot APP (or GCS) publishes the telemetry feeds into an MQTT broker, sending one message per second as specified by the applicable standard in Europe [9]. A bridging/retransmission agent subscribes to the topics used for telemetry, pushing them to the SME platform. This agent may parametrically lose messages and add position noise to the drone surveillance messages, also pushing the feed across a transparent network bridge where the Network emulator (Netem) is deployed. This network emulator provides the means to constrain/disturb the traffic transparently so that both sides of the communication will not be aware of its existence (accordingly with the capabilities already described in BUBBLES deliverables 7.1 [10] and 7.2 [11]). Also, the bridging agent optimizes packet coalescing capabilities, to minimize the retransmission latency overhead, prioritizing latency over throughput.

飞行员应用 (或 GCS) 将遥测信息发布到 MQTT 代理，每秒发送一条消息，如欧洲适用标准 [9] 所规定。一个桥接/重传代理订阅用于遥测的主题，将它们推送到 SME 平台。这个代理可能会参数化地丢

失消息并向无人机监控消息中添加位置噪声，还将信息流推送到部署了网络模拟器 (Netem) 的透明网络桥上。这个网络模拟器提供了限制/干扰流量的手段，使得通信的双方均不会意识到其存在 (符合已在 BUBBLES 交付物 7.1 [10] 和 7.2 [11] 中描述的能力)。此外，桥接代理优化了数据包合并能力，以最小化重传延迟开销，优先考虑延迟而非吞吐量。

Figure 6 shows the internal architecture of this component.

图 6 显示了此组件的内部架构。

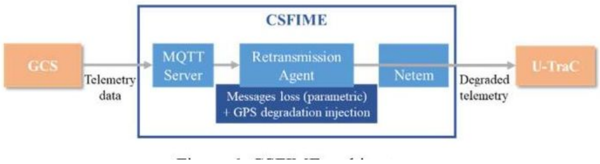


Figure 6. CSFIME architecture

图 6. CSFIME 架构

C. Communication Performance Monitoring (CPM)

C. 通信性能监控 (CPM)

The CPM measures and assesses the performance of the communications evaluating the quality of the communication channel. This component allows to impair and shape the communication channel between the UAS and the tracker to assess the effects of communication performance on the surveillance processing function supporting the provision of separation.

CPM 测量和评估通信性能，通过评估通信通道的质量。此组件允许损害和塑造无人机与跟踪器之间的通信通道，以评估通信性能对监控处理功能的影响，支持分离措施的规定。

The CPM module analyses the communications feed from the UTM side and at the output of the disturbed feed, generating an alert to the UAS operator/pilot in case of severe communications disturbance and to the SMC component to update separation minima accordingly to maintain the target level of safety in the given airspace.

CPM 模块分析来自 UTM 侧的通信信息以及在受干扰信息输出的情况，向无人机操作员/飞行员发出严重通信干扰的警报，并向 SMC 组件更新分离最小值，以保持给定空域的目标安全水平。

This module is implemented by resorting to the instrumentation of the agent, edge broker and core broker components. Edge brokers provide the endpoint of the first communication, ideally within a 1-hop radius from the UAV, while core brokers provide a reliable backbone, designed to provide scalability and reliability properties by means of partitioning mechanisms and distributed geographic points-of-presence. The edge brokers act as repeaters for the core broker infrastructure, designed to constitute the backbone of the communications interfaces for the U-space services. The core broker infrastructure is designed to be redundant, geographically dispersed, and resilient.

本模块通过依赖对代理、边缘代理和核心代理组件的监测来实现。边缘代理提供第一次通信的端点，理想情况下在无人机 1 跳的通信范围内，而核心代理提供可靠的骨干网络，通过分区机制和分布式地理位置点来提供可扩展性和可靠性特性。边缘代理充当核心代理基础设施的中继，旨在构成 U 空间服务通信接口的骨干。核心代理基础设施被设计为冗余、地理分散和具有弹性。

This approach makes it possible to measure and monitor the impact of link quality on the communications flow. Moreover, a network emulator bridge, Netem, which is also part of the CSFIME (see Figure 6), provides communications shaping/impairment capabilities. This emulator is managed by the fault injection tool, which allows configuring, scheduling and triggering network fault/failure situations for controlled experimental validation. A more detailed explanation of the CPM can be found in the document D7.1 Availability Note for the xPM Tool [10].

这种方法可以测量和监控链路质量对通信流的影响。此外，网络仿真桥接器 Netem(也是 CSFIME 的一部分，见图 6)，提供了通信整形/损伤能力。这个仿真器由故障注入工具管理，允许配置、调度和触发网络故障/失败情况，以便进行受控的实验验证。关于 CPM 的更详细解释可以在文档 D7.1 xPM 工具的可用性说明 [10] 中找到。

D. U-space tracking & Conflict detection (U-TraC)

D. U 空间跟踪与冲突检测 (U-TraC)

The U-TraC provides separation management and some other needed U-space services for the test flights. The U-TraC is composed of a tracker, a conflict detection module, and a pseudo-traffic information service.

U-TraC 为试验飞行提供分离管理和一些其他所需的 U 空间服务。U-TraC 由跟踪器、冲突检测模块和伪交通信息服务组成。

This component establishes a connection with the MQTT server to receive and send messages. The UAS telemetry data are received and arranged by the tracker to compute and generate drone tracks, predicting and estimating the drone position and velocity.

此组件与 MQTT 服务器建立连接以接收和发送消息。无人机遥测数据由跟踪器接收并排列，以计算并生成无人机轨迹，预测和估计无人机的位置和速度。

In parallel, the conflict detection module evaluates the scenario by computing pairwise separation between UAS and detects the conflicts between all the UAS that are being tracked. To do so, this module uses the available tracking information, the drone identification information, and the separation minima.

同时，冲突检测模块通过计算无人机之间的成对分离来评估场景，并检测所有被跟踪的无人机之间的冲突。为此，该模块使用可用的跟踪信息、无人机识别信息和分离最小值。

Then, the pseud-traffic information service block aggregates all the available data (drone identification data, tracking data and conflict alerts) and generates a message to send to the pilots (both the pilot command app. and the web interface mentioned at the end of this section).

然后，伪交通信息服务块汇总所有可用数据 (无人机识别数据、跟踪数据和冲突警报)，并生成一条消息发送给飞行员 (包括本节末提到的飞行员指令应用程序和网页界面)。

E. Surveillance Performance Monitoring (SPM)

E. 监控性能监测 (SPM)

The SPM computes performance metrics to assess and evaluate the effects of the surveillance performance due to the degradation of surveillance data.

SPM 计算性能指标，以评估和衡量由于监控数据退化导致的监控性能影响。

The purpose of this component is to determine the effects of failures or degradation on surveillance performance by calculating a set of performance metrics to characterize a surveillance environment qualitatively and quantitatively. Surveillance performance degradation might be the result of multipath, signal shadowing, spoofing, drone hardware/software failures and communication impairments. In the context of this mock-up, this tool is also able to evaluate these metrics and rise an alert in the case that the nominal performance metrics are not met.

此组件的目的是通过计算一组性能指标来确定故障或退化对监控性能的影响，以定性和定量地描述监控环境。监控性能的退化可能是多径效应、信号遮挡、欺骗、无人机硬件/软件故障和通信障碍的结果。在此模拟环境中，此工具还能够评估这些指标，并在名义性能指标未达成时发出警报。

The input of the SPM is the tracking data stream provided by the tracker. This data is received via MQTT protocol and stored. When the required amount of data is received to calculate a statistically relevant analysis, the SPM executes the performance analysis using its internal blocks (see Figure

SPM 的输入是由跟踪器提供的跟踪数据流。这些数据通过 MQTT 协议接收并存储。当接收到足够的数据量以进行统计上有效的分析时，SPM 使用其内部块执行性能分析 (见图)7):

- The reference trajectory reconstruction block computes the reference trajectory from the tracks received and some configuration parameters.

- 参考轨迹重建块根据接收到的轨迹和一些配置参数计算参考轨迹。

- The performance metrics computation block computes the metrics from the reference trajectory reconstructed, the tracking measurements received and the configuration parameters.

- 性能指标计算块根据重建的参考轨迹、接收到的跟踪测量和配置参数计算指标。

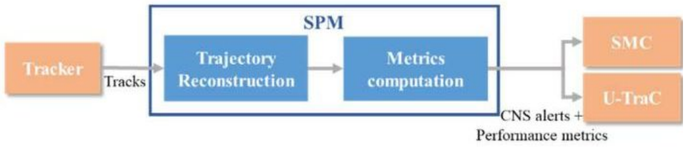


Figure 7. SPM architecture

图 7. SPM 架构

Once the performance metrics are available, these metrics are evaluated to determine if the nominal performance is met. If it is not met, the SPM sends a CNS alert to the pseudo-traffic information service to notify the pilot/GCS and to the SMS component to recalculate the new separation minimum values. More details of the algorithms used in this tool can be found in the document D7.1 Availability Note for the xPM Tool [10].

当性能指标可用后，评估这些指标以确定是否达到名义性能。如果未达到，SPM 向伪交通信息服务发送 CNS 警报，以通知飞行员/GCS，并通知 SMS 组件重新计算新的最小间隔值。有关此工具中使用的算法的更多细节可以在文档 D7.1 xPM 工具可用性说明 [10] 中找到。

F. Separation Minima Calculation (SMC)

F. 最小间隔计算 (SMC)

The SMC consists of a service that, given communication and surveillance performance, sends to the U-TraC the separation minima adapted to the situation. This component includes AI algorithms to compute the separation minima in real-time. The definition of how separation minima are computed is defined in [7] and [12].

SMC 由一个服务组成，该服务在给定通信和监控性能的情况下，向 U-TraC 发送适应情况的分离最小值。这个组件包括 AI 算法，用于实时计算分离最小值。分离最小值的计算方式定义在 [7] 和 [12] 中。

These AI algorithms have been trained before the flights by generating several scenarios by simulation so that in real-time the separation values were updated almost immediately. For each scenario, multiple data sets have been generated, varying the number of UAS flying simultaneously and the position errors introduced in them. Performance metrics are then obtained using the SPM, which are used as inputs to obtain the new separation value for each UAS category.

这些 AI 算法在飞行前通过生成多个模拟场景进行训练，以便在实时中分离值几乎可以立即更新。对于每种场景，都生成了多个数据集，改变了同时飞行的 UAS 数量和引入其中的位置误差。然后使用 SPM 获得性能指标，这些指标作为输入用于获得每个 UAS 类别的新的分离值。

The SMC tool can generate a model that in the presence of new values coming from the SPM tool, can generate new separations depending on the degradation to which the signal is subjected to satisfy the minimum safety requirements established.

SMC 工具可以生成一个模型，在新值来自 SPM 工具的情况下，可以根据信号受到的退化情况生成新的分离值，以满足建立的最低安全要求。

It should be noted that the set of separation minima values are given for traffic class, from the classification defined by BUBBLES in [7] and shown in Table 1, and for each protection volume, as defined in the BUBBLES collision model (see Figure 8).

应该注意的是，分离最小值集合是针对交通类别给出的，由 BUBBLES 在 [7] 中定义的分类，并在表 1 中显示，以及针对每个防护体积，正如 BUBBLES 碰撞模型中定义的 (见图 8)。

TABLE 1. BUBBLES TRAFFIC CLASSIFICATION.

表 1。BUBBLES 交通分类。

<table>
<tr><td rowspan="3">OPEN</td><td rowspan="7">Not carrying people</td><td>A1</td></tr>
<tr><td>A2</td></tr>
<tr><td>A3</td></tr>
<tr><td rowspan="3">SPECIFIC</td><td>SAIL I-II</td></tr>
<tr><td>SAIL III-IV</td></tr>
<tr><td>SAIL V-VI</td></tr>
<tr><td rowspan="2">CERTIFIED</td><td>No passenger</td></tr>
<tr><td>Carrying People</td><td>Passenger</td></tr>
</table>

<table>
<tr><td rowspan="3">开放</td><td rowspan="7">不搭载人员</td><td>A1</td></tr>
<tr><td>A2</td></tr>
<tr><td>A3</td></tr>
<tr><td rowspan="3">特定的</td><td>SAIL I-II</td></tr>
<tr><td>SAIL III-IV</td></tr>
<tr><td>SAIL V-VI</td></tr>
<tr><td rowspan="2">认证的</td><td>无乘客</td></tr>
<tr><td>搭载人员</td><td>乘客</td></tr>
</table>

The collision model used by BUBBLES contemplates four different UAS-centered volumes, thresholds and safety events of decreasing distance to the MAC (called also 'severity' throughout this document), as shown in the figure below. The threshold related to separation minima is the separation threshold. How separation minima are derived from separation thresholds is described in detail also in [7]. Separation thresholds allow computing pairwise separation minima as the sum of the radius of the 'protection' volumes of each aircraft involved in a conflict, according to their traffic category. A conflict happens when the distance to the CPA between a pair of UAS is less than the pairwise separation minima.

BUBBLES 所使用的碰撞模型考虑了四种不同的以无人机系统 (UAS) 为中心的空间体积、阈值和安全事件 (距离 MAC 越来越近，本文档中称为“严重性”)，如下面的图形所示。与最小间隔相关的阈值称为间隔阈值。最小间隔如何从间隔阈值中得出在文献 [7] 中也有详细描述。间隔阈值允许根据冲突中涉及的每架飞机的交通类别，计算成对的最小间隔，作为每个飞机的“保护”体积半径之和。当一对 UAS 之间的 CPA 距离小于成对的最小间隔时，就会发生冲突。

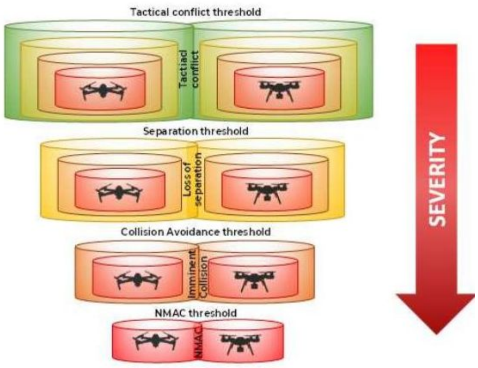


Figure 8. BUBBLES collision model
图 8. BUBBLES 碰撞模型

G. Legal recording

G. 法律记录

This component saves the UAS telemetry data, the tracks, and the conflict alerts for post-processing purposes.

此组件用于保存无人机系统 (UAS) 的遥测数据、轨迹和冲突警报，以供后续处理。

H. Graphical interface

H. 图形界面

The SME platform has also a graphical interface (see Figure 9) where tracks, relevant traffic information and conflict messages generated in a given scenario can be viewed in real-time.

SME 平台还具有一个图形界面 (见图 9)，可以实时查看特定场景中生成的轨迹、相关交通信息和冲突消息。

It is a web-based interface developed in Firebase [5] , which presents a minimalist design, with details and transitions that provide a smooth experience. It is connected to the MQTT server, so all information provided by the interface is updated in real-time.

这是一个基于 Web 的界面，使用 Firebase [5] 开发，具有简约的设计，细节和过渡提供了流畅的体验。它与 MQTT 服务器相连，因此界面提供的所有信息都会实时更新。

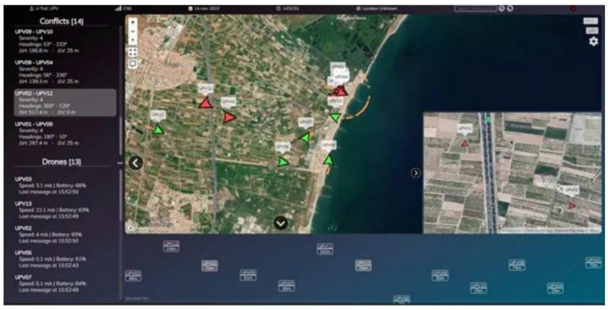


Figure 9. BUBBLES SME platform interface.

图 9. BUBBLES SME 平台界面。

IV. VALIDATION EXERCISE

IV. 验证练习

The BUBBLES concept has been validated using this platform in an experimental exercise by means of test flights. In particular, we have tested the concept of dynamic separation minima adapted to the performance of the communication and surveillance systems, the effectiveness in conflict resolution considering a structured airspace in flight layers [6] and how providing separation management improves safety in terms of avoiding MACs.

使用该平台通过试验飞行进行验证，BUBBLES 概念已经得到验证。特别是，我们测试了动态间隔最小值的概念，以适应通信和监视系统的性能，考虑飞行层 [6] 中的结构化空域在冲突解决中的有效性，以及提供间隔管理如何提高避免 MAC 的安全性。

A. Scenario description

A. 场景描述

The test flights were performed in a rural scenario of 15 km^2 , in an uncontrolled airspace in Puçol, a medium-sized village in the north of Valencia (Spain). The flights involved 7 different experienced operators, including companies, security forces, fire brigades and professional pilots; with 14 different UAS. The traffic density of this scenario represents a short-term medium-density scenario, with 0.93UAS/km^2 . It should be noted that all the UAS flew their missions simultaneously and independently so that the only connection between them was the information displayed on the graphic interface of the pilots' controller application (represented as GCS in Figure 4).

在 15 km^2 的乡村场景中进行了测试飞行，该场景位于西班牙瓦伦西亚北部的一个中等大小的村庄 Puçol 的未受控空域。飞行涉及 7 名经验丰富的操作员，包括公司、安全部队、消防队和专业飞行员；共使用 14 种不同的无人机系统 (UAS)。该场景的交通密度代表了一个短期中等密度场景，具有 0.93UAS/km^2 。值得注意的是，所有 UAS 同时独立地执行它们的任务，因此它们之间的唯一联系是飞行员控制器应用程序图形界面 (在图 4 中表示为 GCS) 上显示的信息。

For each UAS, we assigned a representative mission and operational category (see Table 2). Operations were representative of what could be a future scenario in a suburban area, combining surveillance activities, delivery, or agricultural tasks.

对于每个 UAS，我们分配了一个代表性任务和操作类别 (见表 2)。这些操作代表了一个可能在郊区出现的未来场景，结合了监控活动、配送或农业任务。

TABLE 2. MISSIONS OF THE TEST FLIGHTS.

表 2. 测试飞行的任务。

[6] The concept of structured airspace in flight layers can be found in

[6] 结构化空域的概念在飞行层中可以找到

[5] Firebase is a platform developed by Google for creating web applications.

[5] Firebase 是谷歌开发的一个用于创建网络应用程序的平台。

iD	Mission	Operator	Operational category	UAS
1	Railway inspection	UPV	STS-ES-02	DJI Matrice 300 $_{\text{RTK}}$
2	Road inspection	Police of Valencia	STS-ES-02	DJI Mavic Enterp. Dual
3	Agricultural tasks	UPV	A3	DJI Mavic Enterp. Zoom
4	Surveillance tasks	Police of Valencia	A3	DJI Mavic Enterp. Zoom
5	Delivery-Town	UPV	STS-ES-02	DJI Mavic Enterp. $_{\text{Zoom}}$
6	Delivery-Industrial Park	Police of Valencia	STS-ES-02	DJI Mavic Enterprise Dual
7	Beach surveillance	Police of Benidorm	A3	DJI Mavic Enterp. Zoom
8	Precision agriculture	Police of Valencia	STS-ES-02	DJI Mavic Enterp. Zoom
9	Surveillance of orchards for fire risk	Firefighters of Valencia	STS-ES-02	DJI Mavic Enterp. Advance
10	Rescue of a trapped animal	Firefighters of Valencia	STS-ES-02	DJI Mavic Enterp. Advance
11	Precision agriculture	AsDrón Spain	A3	DJI Phantom 4 PRO
12	Surveillance tasks	UAV works	A3	Valaq Patrol
13	Agricultural tasks	ASD drones	A3	DJI Mavic Enterp. Advance
14	Photogrammetry	Police of Benidorm	A3	DJI Mavic Enterp. Advance

身份识别码	任务	操作员	操作分类	无人航空系统 (UAS)
1	铁路检测	无人驾驶飞行器 (UPV)	STS-ES-02	DJI Matrice 300 $_{\text{RTK}}$
2	道路检测	瓦伦西亚警察	STS-ES-02	DJI Mavic Enterp. 双光版
3	农业任务	无人驾驶飞行器 (UPV)	A3	DJI Mavic Enterp. 变焦版
4	监控任务	瓦伦西亚警察	A3	DJI Mavic Enterp. 变焦版
5	城市配送	无人驾驶飞行器 (UPV)	STS-ES-02	DJI Mavic Enterp. $_{\text{Zoom}}$
6	工业园区配送	瓦伦西亚警察	STS-ES-02	DJI Mavic Enterprise 双光版
7	海滩监控	贝尼多姆警察	A3	DJI Mavic Enterp. 变焦版
8	精准农业	瓦伦西亚警察	STS-ES-02	DJI Mavic Enterp. 变焦版
9	果园火灾风险监测	瓦伦西亚消防员	STS-ES-02	DJI Mavic Enterp. 高级版
10	被困动物的救援	瓦伦西亚消防员	STS-ES-02	DJI Mavic Enterp. 高级版
11	精准农业	AsDrón Spain	A3	DJI Phantom 4 PRO
12	监控任务	无人机作业	A3	Valaq 巡逻
13	农业任务	ASD 无人机	A3	DJI Mavic Enterp. 高级版
14	立体摄影测量	贝尼多姆警察	A3	DJI Mavic Enterp. 高级版

Most of the UAS were DJI multi-rotors between 1 and 9 kg MTOW, and there was also a fixed-wing UAS. The operations were conducted in Open Category, and in Specific Category under Spanish National Standard Scenarios, named

大多数 UAS 是 DJI 多旋翼飞机，最大起飞重量 (MTOW) 在 1 到 9 kg 之间，还有一架固定翼 UAS。这些操作在开放类别下进行，并在西班牙国家标准场景下的特定类别中进行。STS-ES.

Figure 10 shows the operational area where flights were performed, and the reference trajectories planned.

图 10 显示了执行飞行的操作区域以及计划好的参考轨迹。

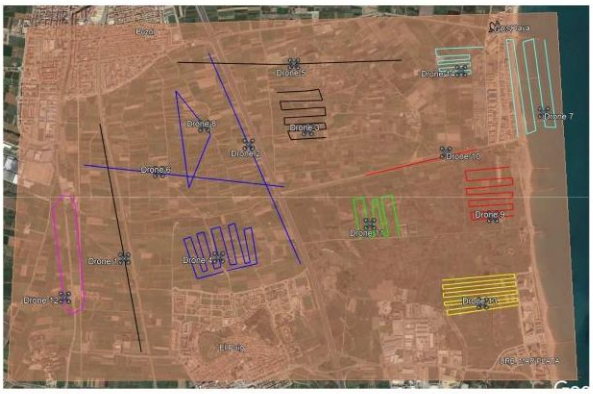


Figure 10. Operational volume and trajectories of test flights.

图 10. 测试飞行的操作体积和轨迹。

B. Exercise description

B. 练习描述

In the test flights, the UAS reported their positioning data to the SME platform, which generated their tracks and detected any potential conflicts by comparing the distances to the CPA between pairs of UASs and their pairwise separation minima according to traffic categories. When a conflict was detected, the platform provided the necessary alerts to the pilots, including the relevant information to solve them.

在测试飞行中，UAS 将其定位数据报告给 SME 平台，该平台生成了它们的轨迹并通过比较 UAS 对之间的最小垂直距离 (CPA) 和根据交通类别确定的它们之间的最小分离距离来检测任何潜在的冲突。当检测到冲突时，平台会向飞行员提供必要的警报，包括解决冲突的相关信息。

During the test flights, conflicts were induced in a controlled way by injecting GPS positioning errors, packet losses and communication channel latencies to simulate an abnormal condition. A fault condition was also simulated by producing a tracker blackout.

在测试飞行中，通过注入 GPS 定位错误、数据包丢失和通信通道延迟以可控的方式诱导冲突，以模拟异常情况。还通过产生跟踪器黑屏来模拟故障条件。

After the flights, the performance of the platform was evaluated in terms of conflict detection and alert declaration, i.e., it was analyzed that the conflict alerts were triggered at the appropriate distances and that the separation minima were correctly updated according to the performance status of the CS systems. We also tested the effectiveness of providing separation management, as well as the use of flight layers to improve safety and efficiency in UAS operations and conflict resolution. All these analyses can be found in Section V.

飞行后，平台的性能通过冲突检测和警报声明来评估，即分析冲突警报是否在适当的距离被触发，以及根据 CS 系统的性能状态正确更新分离最小值。我们还测试了提供分离管理的效果，以及使用飞行层提高无人机操作和安全效率以及在冲突解决中的效果。所有这些分析都可以在第五节找到。

For better representativeness, each mission shown in Figure 10 was flown several times with different configurations, one of them flying the reference trajectories and the other ones with deviations, changing their trajectories and causing conflicts. In addition, at certain instants of time, the CS performance was degraded with the CSFIME component to simulate abnormal conditions.

为了更好的代表性，图 10 中显示的每次任务都进行了多次飞行，使用不同的配置，其中一次飞行参考轨迹，其余的带有偏差，改变它们的轨迹并造成冲突。此外，在某些时刻，通过使用 CSFIME 组件降低 CS 性能来模拟异常情况。

During two days of test flights, a total of 4 tests were carried out, each of which was repeated twice:

在两天的测试飞行中，总共进行了 4 次测试，每次测试都重复了两次:

- Test 1: Flights with autopilot. Each drone was assigned a flight plan and flew at a certain predefined altitude (considering 3 flight layers at 30, 70 and 110 m height) so that all flight plans were strategically deconflicted.
- 测试 1: 自动驾驶飞行。每架无人机被分配了一个飞行计划，并在预定的某个高度 (考虑在 30、70 和 110 m 高度的 3 个飞行层) 飞行，以便所有飞行计划都能战略性地避免冲突。
- Test 2: Manual flights following the reference trajectory. Each drone had its mission defined, as well as its flight level (traffic divided into 3 layers at 30,70 and 110 m height).
- 测试 2: 手动飞行，遵循参考轨迹。每架无人机都有其定义的任务以及其飞行高度 (交通分为 3 个层，在 30、70 和 110 m 高度)。
- Test 3: Manual flights following the reference trajectory. Each drone had its mission defined, but in this case, all UAS flew in the same flight layer (between 65 and 75 m altitude).
- 测试 3: 手动飞行，遵循参考轨迹。每架无人机都有其定义的任务，但在这种情况下，所有无人机都在同一飞行层飞行 (在 65 和 75 m 高度之间)。
- Test 4: Manual flights following the reference trajectory. Each drone had its mission defined, and in this case, flight levels were completely free.
- 测试 4: 手动跟随参考轨迹的飞行。每个无人机都有其定义的任务，在这种情况下，飞行高度完全自由。

As mentioned above, in case of conflict, pilots were shown an alert on the controller indicating the other UAS in conflict, the horizontal and vertical distance to it and a simple suggestion of a maneuver to solve it (ascend or descend). In case of multiple conflicts, the alert of the most severe conflict was displayed, i.e., the closest and the most urgent to solve.

如上所述，在冲突的情况下，飞行员会在控制器上看到一个警报，显示与其冲突的其他无人机，与其的水平距离和垂直距离，以及一个简单的解决冲突的建议 (上升或下降)。在多个冲突的情况下，显示最严重冲突的警报，即最近且最需要立即解决的冲突。

Due to the lack of right-of-way rules for UAS, the proposed resolution maneuver was simple: when two drones came into conflict, the one above would ascend and the one below would descend. In addition, the structured layered airspace concept facilitated conflict resolution through vertical maneuvers. So, in all cases, pilots had to solve conflicts with vertical maneuvers. They had to give priority to the proposed maneuver unless there was a setback such as the conflicting drone doing the same maneuver (e.g. pilot 1 was told to descend and pilot 2 also descended because he misinterpreted the information, so the conflict was not solved in a short period of time, in which case pilot 1 was free to solve the conflict as he considered to avoid an imminent collision).

由于缺乏无人机优先权规则，提出的解决机动动作很简单: 当两架无人机发生冲突时，上面的无人机上升，下面的无人机下降。此外，结构化的分层空域概念通过垂直机动动作促进了冲突的解决。因此，在所有情况下，飞行员必须使用垂直机动来解决冲突。他们必须优先考虑提出的机动，除非出现挫折，例如冲突的无人机执行相同的机动 (例如，飞行员 1 被告知下降，飞行员 2 也下降了，因为他误解了信息，所以冲突在短时间内没有得到解决，在这种情况下，飞行员 1 可以自由地解决冲突，以避免即将发生的碰撞)。

The main objectives of this validation exercise are: (1) to ensure that the SME platform detects conflicts and gives alerts with suggestive maneuvers to pilots; (2) to check if the separation minima are properly adapted to the environment based on the CS services performance, (3) to test whether the separation provision prevents conflicts from becoming a MAC, and (4) to assess whether the use of flight layers improves or facilitates conflict resolution.

本次验证练习的主要目标有:(1) 确保 SME 平台能够检测到冲突并向飞行员提供带有建议机动的警报；(2) 检查基于 CS 服务性能，分离最小值是否适当地适应了环境；(3) 测试分离规定是否能够防止冲突演变成 MAC；(4) 评估使用飞行层是否改进或促进了冲突的解决。

V. VALIDATION RESULTS

V. 验证结果

After the flights, a post-analysis of the results obtained with the BUBBLES SME platform was made.

飞行后，对使用 BUBBLES SME 平台获得的结果进行了后分析。

Figure 11 shows the conflict distribution during all test flights for each time instant, i.e. the number of unique conflicts detected per minute.

图 11 显示了所有测试飞行期间每个时间点的冲突分布，即每分钟检测到的唯一冲突数量。

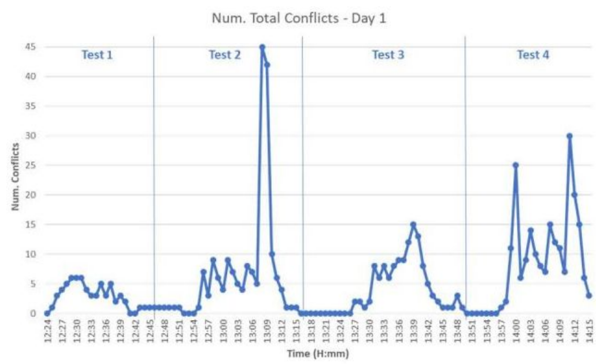


Figure 11. Number of conflicts per instant time and test.

图 11. 每个瞬时时间和测试中的冲突数量。

In Figure 11, it is highlighted the peak of conflicts in test 2 due to a tracker stop, simulating a fault condition. Due to this failure, the separation minima increased significantly (see Figure 15, the increase in the tactical conflict separation threshold between 13:00 and 13:15) to preserve the level of safety, thus increasing the number of conflicts. This peak demonstrates that, in the absence of separation provision, separation distances have to increase dramatically to keep the safety level of the scenario constant, which greatly increases the number of conflicts. In turn, increasing the number of conflicts so much is socially unacceptable, so the number of drones operating in any given volume would have to be reduced, which would be an inefficient use of airspace. This demonstrates that leaving separation management in the hands of pilots would not be sufficient to ensure safe and efficient use of airspace, so such a service is needed.

在图 11 中，突出了测试 2 中由于跟踪器停止导致的冲突高峰，模拟了故障条件。由于这个故障，分离最小值显著增加 (见图 15，13:00 至 13:15 之间战术冲突分离阈值的增加)，以保持安全水平，从而增加了冲突数量。这个高峰表明，在没有分离规定的情况下，分离距离必须大幅增加以保持场景的安全水平，这将极大地增加冲突数量。反过来，如此多地增加冲突在社会上是不被接受的，因此，在任何给定体积内运行的无人机数量必须减少，这将是对空域的不高效使用。这表明，将分离管理留给飞行员将不足以确保空域的安全和高效使用，因此需要此类服务。

Table 3 summarizes the total number of conflicts in each of the tests performed and the average duration of conflicts, as well as the percentage of the conflicts solved.

表 3 总结了每次测试中发生的总冲突数以及冲突的平均持续时间，以及解决的冲突百分比。

TABLE 3. NUMBER OF CONFLICTS PER TEST RESULTS.

表 3. 每次测试结果中的冲突数量。

Test	Conflicts detected	Mean conflicts duration (s)	Conflicts solved (%)
1	27	82.92	96
2	109	47.52	99
3	76	37.70	99
4	158	21.75	97

测试	检测到冲突	平均冲突持续时间 (秒)	解决的冲突百分比 (%)
1	27	82.92	96
2	109	47.52	99
3	76	37.70	99
4	158	21.75	97

As can be seen in Table 3, test 1 had the lowest number of conflicts, as they flew on autopilot and all flight plans were deconflicted in the pre-operational phase.

如表 3 所示，测试 1 的冲突数量最少，因为它们使用自动驾驶飞行，所有飞行计划在预操作阶段就已经解冲突。

Then, test 4, in which the drones flew at free altitudes, had the highest number of conflicts. In contrast, flying in assigned flight layers reduced the number of conflicts by half.

然后，测试 4 中，无人机在自由高度飞行，冲突数量最多。相比之下，在指定的飞行层中飞行将冲突数量减少了一半。

In tests 2 and 3 there is approximately the same number of conflicts, although when flying all UAS in the same layer the conflicts were shorter because they were easier to solve, as there was no other drone above or below the drones in conflict and were quickly solved with a vertical maneuver.

在测试 2 和测试 3 中，冲突数量大致相同，尽管当所有无人机在同一层飞行时，冲突时间更短，因为它们更容易解决，因为没有其他无人机在冲突中的无人机上方或下方，且可以通过垂直机动快速解决。

Thus, flying in structured airspace is arguably safer in terms of the number of conflicts, although solving them requires a few seconds more on average. When layers are separated by at least 3 times the height of the aircraft protection volume, there is enough distance to solve conflicts without causing new ones, thus allowing more efficient use of airspace compared to unstructured or free-altitudes airspace.

因此，在结构化空域中飞行在冲突数量方面可以说是更安全的，尽管解决这些冲突平均需要几秒钟的时间。当各层之间的间隔至少为飞机保护体积的 3 倍时，有足够的距离解决冲突而不会产生新的冲突，因此与未结构化或自由高度的空域相比，可以更有效地使用空域。

Looking at the last column of Table 3, almost all the conflicts were successfully solved thanks to the alerts sent to the pilots, except for some specific cases where the tests ended before they could be solved and in the post-processing, exact times have been taken, leaving out the resolution times. Another small percentage of cases were momentary MQTT server crashes or loss of signal.

查看表 3 的最后一列，几乎所有的冲突都因为向飞行员发送了警报而成功解决，除了某些特定情况，在这些情况下测试在冲突解决之前就结束了，并且在后处理中，已经记录了确切的时间，省略了解决时间。另外一小部分情况是 MQTT 服务器短暂崩溃或信号丢失。

Analyzing the conflicts per severity, i.e. depending on what protection volume (as defined by BUBBLES [7]) is infringed, more than 95% of the conflicts were tactical conflicts (TC), and only 2.97% reached the loss of separation (see TABLE 4).

分析按严重性划分的冲突，即取决于侵犯了哪个保护体积 (如 BUBBLES [7] 所定义的)，超过 95% 的冲突是战术冲突 (TC)，只有 2.97% 达到了失去间隔 (见表 4)。

TABLE 4. NUMBER OF CONFLICTS PER TYPE OF CONFLICT

表 4。按冲突类型划分的冲突数量

	Num. Conflicts	Percentage
NMAC (severity1)	2	0.54%
Imminent collision (sev. 2)	5	1.35%
Loss of separation (sev. 3)	11	2.97%
Tactical conflict (sev. 4)	352	95.14%
Total	370	

	冲突数量	百分比
NMAC (severity1)	2	0.54%
即将发生的碰撞 (严重性 2)	5	1.35%
分离损失 (严重性 3)	11	2.97%
战术冲突 (严重性 4)	352	95.14%
总计	370	

This demonstrates that issuing an alert to pilots is very useful to solve potential conflicts and that the tactical mitigation barrier prevented more than 95% of tactical conflicts from evolving into imminent collisions, at which point Collision Avoidance would come into play.

这表明向飞行员发出警报对于解决潜在的冲突非常有用，并且战术缓解屏障阻止了超过 95% 的战术冲突演变成即将发生的碰撞，在这一点上碰撞避免将发挥作用。

Below are two graphs showing the CPA distance of each of the detected higher-severity safety events (severity 1 and 2) versus the collision threshold. That is, they show the minimum distance at which the conflicting drone pair stayed (green dot) compared to the distance considered as collision (blue line). The grey line shows the margin in meters between the CPA and the collision threshold (also named Mid-Air Collision - MAC).

下面是两个图表，显示了检测到的每个更严重安全事件 (严重性 1 和 2) 的最近点距离 (CPA) 与碰撞阈值的关系。也就是说，它们显示了冲突的无人机对保持的最小距离 (绿色点) 与被认为是碰撞的距离 (蓝色线) 相比。灰色线显示了最近点距离与碰撞阈值 (也称为空中相撞 - MAC) 之间的余量 (以米为单位)。

The first graph (Figure 12) shows the two NMAC events, considered Near-Mid-Air Collisions (NMAC), in which the innermost protection volume had been violated, according to the collision model developed by BUBBLES [7]. The second graph (Figure 13) shows the five 'Imminent collision' safety events, in which the minimum distance of the second innermost protection volume was violated.

第一个图表 (图 12) 显示了两次 NMAC 事件，即根据 BUBBLES [7] 开发的碰撞模型中被视为接近空中碰撞 (NMAC) 的事件，其中最内层保护体积已被违反。第二个图表 (图 13) 显示了五次“即将碰撞”的安全事件，其中第二内层保护体积的最小距离被违反。

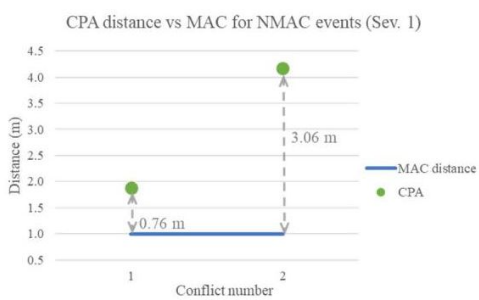


Figure 12. NMAC events detected vs collision threshold.

图 12. NMAC 事件检测与碰撞阈值。

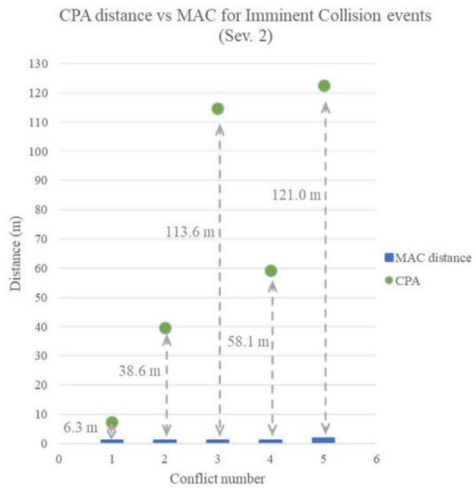


Figure 13. Imminent collisions detected vs collision threshold.
图 13. 即将碰撞检测与碰撞阈值。

As can be seen in Figure 12, in the second conflict the distance between drones was more than 3 times the distance of the threshold considered MAC. The case of the first conflict is because the takeoff point of that pair of drones was the same, so at the time of starting the test they were already in conflict, and this was solved by ascending with a time delay.

如图 12 所示，在第二次冲突中，无人机之间的距离是认为的 MAC 距离阈值的三倍以上。第一次冲突的情况是因为那对无人机的起飞点是相同的，所以在测试开始时它们已经处于冲突状态，并且通过延迟上升时间解决了冲突。

In the case of Figure 13, the MAC distance of conflict 5 stands out, which is greater than the rest since the pair of drones involved were of different categories (A3 and SAIL III). The case of the first conflict has the same explanation as conflict 1 in the previous graph.

在图 13 的情况下，冲突 5 的 MAC 距离很突出，因为它大于其余的，因为涉及的无人机对属于不同的类别 (A3 和 SAIL III)。第一次冲突的情况与上一个图表中冲突 1 的解释相同。

As can be seen, from imminent collision events onwards, the CPA distances are already quite large and there is enough margin to resolve conflicts without reaching a collision. Moreover, since the pilot was alerted in case of conflict, few cases reached this conflict event, as most of them were resolved earlier.

可以看到，从即将碰撞事件开始，CPA 距离已经相当大，有足够的空间来解决冲突而不会发生碰撞。此外，由于在冲突情况下飞行员会收到警报，所以很少达到这种冲突事件，因为大多数冲突在早期就已经得到解决。

Then, another technical analysis was made to check if separation minima were properly updated according to the CS degradation. Figure 14 shows the injected degradations by hours, and Figure 15 depicts how this has affected the separation minima.

然后，进行了另一项技术分析，以检查是否根据 CS 退化正确更新了分离最小值。图 14 显示了按小时注入的退化，而图 15 展示了这对分离最小值的影响。

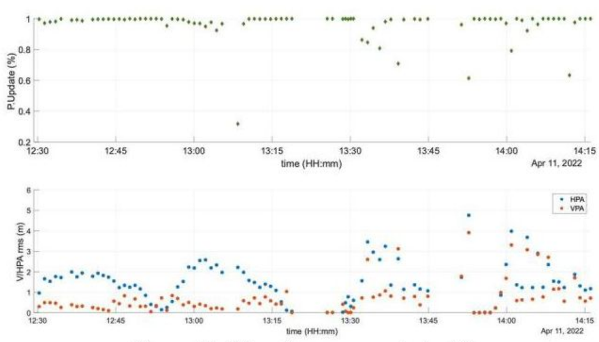


Figure 14. CS performance per instant time.

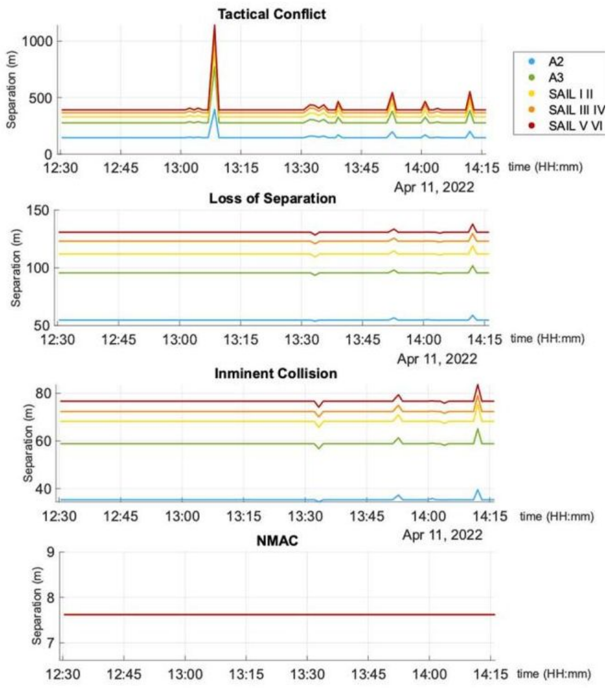


Figure 15. Separation Minima per instant time

As can be seen, NMAC distance is not affected by CNS performance. This is because is an aircraft size-dependent parameter and is a fixed value [14]. In contrast, the other 3 distances are affected when performance is degraded. The GPS degradation affects the Vertical and Horizontal Positioning Accuracy (VPA/HPA) and packet loss affects the message update probability (P_U) , i.e. the % of drone telemetry reports that have arrived at the tracker.

如所见，NMAC 距离不受 CNS 性能影响。这是因为它是一个依赖于飞机尺寸的参数，而是一个固定值 [14]。相反，当性能降低时，其他 3 个距离会受到影响。GPS 降级会影响垂直和水平定位精度 (VPA/HPA)，而数据包丢失会影响消息更新概率 (P_U) ，即到达跟踪器的无人机遥测报告的 % 。

When VPA/HPA worsens compared to the predefined threshold, which has been set at 3 m for the Horizontal dimension and 3.5 m for the Vertical dimension, the Imminent Collision distance is affected and therefore the other two external distances are affected as well. In the case of the P_U , when this went below 95% it meant that the tracker had not received as many messages as it should have, causing the tactical conflict distance, to increase, as this parameter adds a time buffer.

当 VPA/HPA 相对于预定义阈值恶化时，对水平维度的设置为 3 m ，对垂直维度的设置为 3.5 m ，即将发生的碰撞距离会受到影响，因此另外两个外部距离也会受到影响。在 P_U 的情况下，当其低于 95% 时，意味着跟踪器没有接收到应有的那么多消息，导致战术冲突距离增加，因为此参数增加了一个时间缓冲。

So, dynamic separation minima were properly applied during test flights and guaranteed that the TLS was achieved.

因此，动态间隔最小值在测试飞行中得到了正确应用，并确保了 TLS 的实现。

VI. CONCLUSIONS

VI. 结论

This paper presents a brief description of the separation management concept and its prototypical implementation, the BUBBLES Separation Management Environment platform, supporting the separation provision by means of UTM proposed by BUBBLES. Then, the present paper defines the test flights conducted to validate that platform, especially to validate the CS performance monitoring and the dynamic separation minima computation, and shows the results obtained.

本文简要介绍了分离管理概念及其原型实现——BUBBLES 分离管理环境平台，该平台通过 BUBBLES 提出的 UTM 支持分离规定。然后，本文定义了为验证该平台进行的测试飞行，尤其是验证 CS 性能监控和动态间隔最小值计算，并展示了获得的结果。

Regarding the BUBBLES concept, this has been the first European project, funded by SESAR, to address the problem of how to deal with the separation provision in UTM airspaces and what information would need to be provided to UAS users or service providers to manage separation between aircraft, including manned aviation.

关于 BUBBLES 概念，这是第一个由 SESAR 资助的欧洲项目，旨在解决如何在 UTM 空域中处理分离规定的问题，以及需要向 UAS 用户或服务提供商提供哪些信息来管理飞机之间的分离，包括有人驾驶航空。

As for the test flights, it was the first time that so many UAS were flown simultaneously, controlled by different pilots, in a relatively small area of 15 km^2 , and all of them connected to a platform providing UTM pseudo-services. Thus, the flights have been a representation of what could be the future of drones in urban and rural environments, and to see how necessary it is to provide UTM services to increase the safety and efficiency of the airspace.

至于测试飞行，这是第一次在相对较小的区域 15 km^2 内，由不同的飞行员同时操控如此多的无人机系统 (UAS)，并且它们都连接到了提供无人机交通管理 (UTM) 伪服务的平台。因此，这些飞行展示了无人机在城市和乡村环境中的未来可能形态，以及提供 UTM 服务以提升空域安全和效率的必要性。

Concerning the results, as seen in the previous section, the platform was able to detect potential conflicts and prevent them from escalating in higher-severity conflict event or even reaching a mid-air collision. In addition, the dynamic separation minima allowed for adaptation to the situation at any given time, depending on the performance of the communications and surveillance infrastructure in this case, so that the target level of safety of the scenario was always maintained. Then, with the tracking stop peak of test 2, the non-provision of separation has a negative effect on the safety and efficiency of the airspace. In order to maintain the safety level, the minimum separations would have to be greatly increased, and therefore the number of conflicts is so high that it becomes unacceptable, and the capacity of the operational volume would have to be decreased. As for the horizontal organization of the airspace, BUBBLES proposed a structure arranged in horizontal layers which favor the resolution of conflicts by means of vertical maneuvers, as well as the organization of traffic according to its risk level, thus reducing the number of conflicts.

关于结果，如前一部分所见，该平台能够检测到潜在的冲突并防止其升级为更严重冲突事件，甚至避免发生空中碰撞。此外，动态分离最小值允许根据通信和监视基础设施的性能在任何给定时间适应情况，从而始终维持场景的目标安全水平。在测试 2 的跟踪停止峰值时，不提供分离会对空域的安全和效率产生负面影响。为了维持安全水平，最小分离值将不得不大幅增加，因此冲突数量如此之高以至于变得不可接受，并且运营空间的容量将不得不降低。至于空域的水平组织，BUBBLES 提出了一种水平层状结构，这有利于通过垂直机动解决冲突，以及根据风险水平组织交通，从而减少冲突数量。

All these show the need to provide a separation management service to all users flying in UTM airspaces, especially in urban environments where safety is a key parameter. Furthermore, providing a separation management service would help to make the use of airspace more efficient and safer, which would lead to promoting the social acceptance of UAS use in urban or highly populated environments.

所有这些都显示了为所有在 UTM 空域飞行的用户提供分离管理服务的必要性，特别是在安全是关键参数的城市环境中。此外，提供分离管理服务将有助于使空域的使用更加高效和安全，这将促进社会对在城市或人口密集环境中使用无人机的社会接受度。

ACKNOWLEDGMENT

致谢

This research was conducted under the BUBBLES project (Grant 893206) supported by SESAR Joint Undertaking under European Union’s Horizon 2020 research and innovation programme. BUBBLES consortium is formed by Universitat Politècnica de València (UPV), Universidade de Coimbra (UC), Università degli Studi di Rome La Sapienza (UNIROMA1), INDRA and EUROCONTROL.

该研究是在 BUBBLES 项目 (资助号 893206) 下进行的，该项目由 SESAR 联合企业支持，属于欧盟地平线 2020 研究和创新计划。BUBBLES 财团由瓦伦西亚理工大学 (UPV)、科英布拉大学 (UC)、罗马大学 La Sapienza(UNIROMA1)、INDRA 和 EUROCONTROL 组成。

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