Systematic Review of Collision-Avoidance Approaches for Unmanned Aerial Vehicles

无人机避障方法的系统性回顾

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Abstract-Over the past decade, unmanned aerial vehicles (UAVs) have demonstrated increasing attention and promise. They demonstrate great potential for application in both civilian and military fields. In this context, collision-avoidance (CA) approaches play an extremely important role in collaborative and noncollaborative UAVs in a common airspace for reliable and safe operation. In this article, we give an analysis and description of the CA functions, including the CA process, state sensing, conflict detection, and conflict resolution. Then, an overview of the recent progress in CA technologies is systematically provided, particularly in terms of sensing techniques, conflict detection, and conflict resolution. The state-sensing methods include ground-based and air-based sensing technologies, and cooperative and non-cooperative sensing. The conflict-detection methods contain conflict detection with certainty and without certainty. The conflict-resolution methods include methods for individual UAVs and for UAV formation. In addition, several challenging problems are introduced to develop a lucid research direction. This review gives a unique perspective and contributes toward the further development of CA approaches for UAVs.

摘要-在过去的十年里，无人机 (UAVs) 受到了越来越多的关注，并显示出巨大的应用潜力。它们在民用和军事领域都显示出巨大的应用前景。在此背景下，避障 (CA) 方法在协作和非协作无人机在通用空域中的可靠和安全运行中发挥着极其重要的作用。在本文中，我们对避障功能进行了分析和描述，包括避障过程、状态感知、冲突检测和冲突解决。接着，系统地提供了最近在避障技术方面的进展概述，特别是在感知技术、冲突检测和冲突解决方面。状态感知方法包括基于地面和基于空中的感知技术，以及合作和非合作感知。冲突检测方法包括确定性的冲突检测和非确定性的冲突检测。冲突解决方法包括针对单个无人机和无人机编队的方法。此外，还介绍了几个具有挑战性的问题，以明确研究方向。本综述提供了一个独特的视角，有助于无人机避障方法的进一步发展。

Index Terms-Collision avoidance (CA), conflict detection, conflict resolution, sensing technologies, unmanned aerial vehicle

索引术语-避障 (CA)，冲突检测，冲突解决，感知技术，无人机 (UAV).

I. INTRODUCTION

I. 引言

UNMANNED aerial vehicles (UAVs) refer to aircraft with- out a pilot on board [1]-[4]. Such vehicles are controlled either autonomously using attached microprocessors or telemetrically by an operator on the ground [5]-[8]. The development of UAVs is of significant interest to many governmental and military organizations around the world. Furthermore, according to the Federal Aviation Administration, there could be more than 7 million UAVs flying in the United States by 2020 [9]. It should be noted that UAV is the most common general term; remotely piloted aircraft emphasizes the importance of human-in-the-loop control and the characteristics of remote driving; the drone is

无人驾驶飞行器 (UAVs) 指的是没有驾驶员在机上的飞行器 [1]-[4]。这类飞行器可以通过附带的微处理器自主控制，或者通过地面的操作员遥测控制 [5]-[8]。UAVs 的发展引起了世界各地许多政府及军事组织的极大兴趣。此外，根据联邦航空管理局的数据，到 2020 年，美国可能会有超过 700 万架 UAVs 在空中飞行 [9]。需要注意的是，UAV 是最常见的通用术语；遥控飞行器强调的是人在回路控制的重要性和远程驾驶的特点；而无人机这个词则被公众广泛使用，主要指常见的多旋翼无人机。

a word widely used by the public, mostly used for common multipropeller drones.

是公众广泛使用的词汇，主要用于普通多旋翼无人机。

A. UAVApplication

A. 无人机应用

The UAVs used by military forces to search and destroy have attracted growing scrutiny in recent years. They are considered superior to manned aircraft due to several features, the most prominent of which is their unobstructed implementation in high-risk and long-endurance missions [10]. The use of UAVs is also increasing rapidly in many civil domains, including for real-time monitoring, remote sensing, emergency response, mapping, policing, search and rescue, goods delivery, firefighting, precision agriculture, disease control, and scientific endeavors, among others [11]-[21]. For instance, UAVs can be used to carry sensors to monitor air quality index (AQI) and help construct an AQI map in corresponding areas [13]. The National Aeronautics and Space Administration conducted hurricane and climate studies using Northrop Grumman's Global Hawk, which can reach an altitude of nearly 20 km (which is a no-fly zone for commercial aircraft) [22]. UAVs can have many different shapes, mechanisms, configurations, and characteristics. Moreover, as UAVs are usually developed for specific purposes, their hardware and software design can be varied based on the task requirements [23].

军方用于搜索和摧毁目标的无人机近年来受到了越来越多的关注。由于它们的几个特点，比如在执行高风险和长续航任务时不受阻碍，它们被认为比有人驾驶飞机更优越 [10]。无人机的使用在许多民用领域也正在迅速增加，包括实时监控、远程传感、紧急响应、绘图、警务、搜救、货物运输、消防、精准农业、疾病控制以及科学研究等 [11]-[21]。例如，无人机可以携带传感器来监测空气质量指数 (AQI)，并帮助在相应区域构建 AQI 地图 [13]。美国国家航空航天局使用诺斯罗普 · 格鲁门公司的全球鹰进行了飓风和气候研究，该无人机能够达到近 20 km 的高空 (这是商业飞机的禁飞区)[22]。无人机可以有许多不同的形状、机构、配置和特性。此外，由于无人机通常是为了特定目的而开发的，它们的硬件和软件设计可以根据任务需求而有所不同 [23]。

An essential aspect of UAV autonomy is its ability to resolve encounters, which is known as collision avoidance (CA). With the gradual opening of low-altitude airspace to UAVs, one of the most important strategic challenges is to find efficient methods to manage available airspace capacity and ensure a sustainable air-transportation system, especially in terminal maneuvering areas where the number of flights is very high. Therefore, UAVs should follow effective and standardized CA approaches to navigate civil airspace routinely and safely. In practical applications, UAVs may encounter different kinds of obstacles, such as mountains, trees, buildings, and other aircraft. Fig. 1 depicts a case scenario of several UAVs with different functions in a real city environment, e.g., patrol, security, delivery, auxiliary work, entertainment, photographing, and so on [24]. It should be noted that when obstacle buildings are densely arranged, it is necessary to envelop UAVs according to their shape and performance and set them at a safe distance from each other.

无人机自主性的一个基本方面是它解决相遇的能力，这被称为避障 (CA)。随着低空空域逐渐向无人机开放，最重要的战略挑战之一是找到有效的方法来管理可用空域容量，并确保可持续的航空运输系统，特别是在航班数量非常高的终端机动区域。因此，无人机应遵循有效且标准化的避障方法，以常规和安全的方式在民用空域中导航。在实际应用中，无人机可能会遇到不同类型的障碍物，例如山脉、树木、建筑物和其他飞行器。图 1 描述了在真实城市环境中具有不同功能的多个无人机的案例场景，例如巡逻、安全、配送、辅助工作、娱乐、摄影等 [24]。应注意，当障碍建筑物密集排列时，需要根据无人机的形状和性能将它们包围，并将它们彼此保持在一个安全距离。

For commercial aircraft, the traffic alert and collision-avoidance system (TCAS) is considered as the last resort to prevent midair collisions (MACs) and significantly reduce near

对于商业飞机而言，交通警报和避障系统 (TCAS) 被认为是防止空中相撞 (MACs) 的最后手段，并显著减少接近事故。

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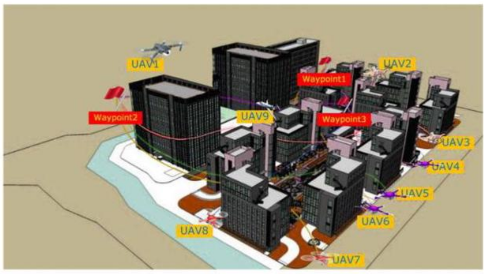

Fig. 1. Conceptual model of several UAVs in a typical urban environment.
图 1. 几个无人机在典型城市环境中的概念模型。

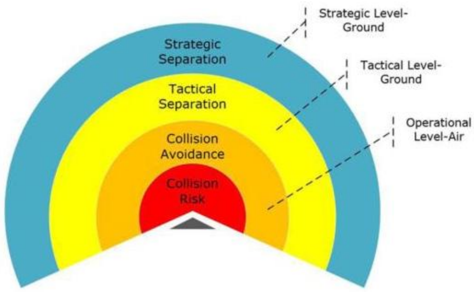

Fig. 2. Layers of UAV conflict management [30].
图 2. 无人机冲突管理的层次结构 [30]。

MACs [25], [26]. The main functions of TCAS are to communicate detected threats to the pilot and assist in resolving the said threats by generated avoidance maneuvers [27]. Thus, UAVs should be capable of autonomously planning trajectories in real time to avoid collisions with obstacles and other aircraft. Currently, any UAV that enters common airspace should be capable of sensing and avoiding potential collisions [28].

MACs [25], [26]。TCAS 的主要功能是将检测到的威胁通知飞行员，并通过生成避障机动来协助解决这些威胁 [27]。因此，无人机应能够自主规划实时轨迹，以避免与障碍物和其他飞行器碰撞。目前，任何进入公共空域的无人机都应具备感测和避免潜在碰撞的能力 [28]。

B. Conflict Management

B. 冲突管理

In air-traffic management (ATM), the term ”conflict management” is used to discuss the flight trajectories of manned and unmanned aircraft to avoid potential collision hazards [29]. For the UAVs discussed in this review, ATM is implemented in three different layers: strategic separation, tactical separation, and CA, as illustrated in Fig. 2 [30]. Strategic separation is employed at a strategic level for airspace planning. Typically, the primary focus in this step is to address management problems in air-traffic flow, such as the programming of all involved trajectories using a comparatively longer look-ahead time. Tactical separation is employed at a tactical level as a planning system to contain interference factors caused by occasional events (e.g., a certain flight is temporarily added, while other nearby flights need to be adjusted) that cannot be forecast with enough accuracy by long-term flight plans. CA is employed at an operational level to resolve upcoming threats; it should be noted that this is not a planning system. Generally, it is employed in a class of airborne devices incorporating related algorithms; these devices operate independently without the assistance of ground-based control systems.

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在空中交通管理 (ATM) 中，术语“冲突管理”用于讨论有人驾驶和无人驾驶飞机的飞行轨迹，以避免潜在的碰撞危险 [29]。本文讨论的无人机 (UAVs) 中，ATM 在三个不同的层面实施: 战略隔离、战术隔离和防撞 (CA)，如图 2 所示 [30]。战略隔离在战略层面用于空域规划。通常，这一步骤的主要关注点是解决空中交通流中的管理问题，例如使用相对较长的时间前瞻来规划所有相关轨迹。战术隔离在战术层面作为规划系统，用于包含由于偶尔事件 (例如，临时增加特定航班，而附近的航班需要调整) 引起的干扰因素，这些因素无法通过长期飞行计划准确预测。防撞 (CA) 在操作层面用于解决即将到来的威胁；需要注意的是，这不是一个规划系统。通常，它被应用于一类包含相关算法的机载设备中；这些设备在没有地面控制系统辅助的情况下独立运行。

Weaknesses in strategic separation are usually resolved by tactical separation, and tactical separation-failure scenarios can be dealt with by the operational avoidance of potential collisions. Thus, by discussing and improving the performance of CA approaches, it may be possible to avoid failures hidden behind a lack of integration among trajectory management, separation management, and conflict management when applied to different ATM scenarios.

战略隔离的弱点通常通过战术隔离来解决，战术隔离失败的情景可以通过操作上避免潜在碰撞来处理。因此，通过讨论并改进 CA 方法的性能，可能避免在将不同 ATM 场景应用于轨迹管理、隔离管理和冲突管理之间的整合不足时隐藏的失败。

C. Main Work

C. 主要工作

For UAVs, the basic idea of CA involves monitoring the environment for any encounter (including cooperative/noncooperative aircraft and stationary/moving obstacles) in shared airspace. CA approaches are the key to guaranteeing seamless and safe integration of UAVs. A review of CA technical development is presented in this article from the standpoints of sensing technology, conflict detection, and conflict resolution. The existing approaches corresponding to these three aspects are also summarized and analyzed.

对于无人机而言，CA 的基本思想是监控共享空域中的任何遭遇 (包括合作/非合作飞机和静止/移动障碍物)。CA 方法是保证无人机无缝和安全集成的关键。本文从感知技术、冲突检测和冲突解决的角度介绍了 CA 技术发展的回顾。这三个方面对应的存在方法也得到了总结和分析。

D. Major Contributions

D. 主要贡献

This review tentatively organizes this survey work based on the workflow of CA logic functions. The focus of this article is to provide an analysis and description of the CA functions, including the CA process, state sensing, conflict detection, conflict resolution, and introduce several challenging problems to develop a lucid research direction. The major contributions of this review are as follows:

本综述尝试根据冲突避免 (CA) 逻辑函数的工作流程来组织本次调研工作。本文的重点是对 CA 功能进行分析和描述，包括 CA 过程、状态感知、冲突检测、冲突解决，并介绍几个具有挑战性的问题，以明确研究方向。本综述的主要贡献如下:

1) Present researchers and system designers with a unique perspective on CA process and functions for UAVs.

1) 为研究人员和系统设计者提供了一个关于无人机 (UAVs)CA 过程和功能的独特视角。

2) Discuss the various aspects of CA approaches as well as their advantages and disadvantages during threat resolution.

2) 讨论了 CA 方法在威胁解决过程中的各个方面以及其优缺点。

3) Summarize the major challenges for facilitating the development of CA approaches to promote the widespread use of UAVs with reliable and safe operations.

3) 概括了促进 CA 方法发展的主要挑战，以推动可靠和安全操作的无人机的广泛应用。

E. Organization

E. 组织结构

The rest of this article is arranged as follows. CA functions are analyzed in detail in Section II. In Section III, different sensing technologies, as the basis for state-information acquisition, are reviewed for constructing the framework of CA approaches. Conflict-detection methodologies that take UAV dynamics and external disturbances into account are categorized and described in Section IV. Conflict-resolution approaches are surveyed in Section V. Based on an extensive survey of the available literature and current research hotspots, several research challenges are proposed for CA development in Section VI. Finally, Section VIII presents the concluding remarks of this article.

本文其余部分安排如下。第二节详细分析了 CA 功能。第三节回顾了不同的感知技术，作为状态信息获取的基础，用于构建 CA 方法框架。第四节对考虑无人机动态和外部干扰的冲突检测方法进行了分类和描述。第五节调查了冲突解决方法。基于对现有文献和当前研究热点的广泛调研，第六节提出了 CA 发展的几个研究挑战。最后，第八节呈现了本文的结论性 remarks。

II.CA FUNCTION

II.CA 功能

In general, the underlying CA functions are similar, although the specific models and alerting thresholds of different approaches are different. A framework that articulates basic CA functions is used to categorize CA approaches. In this framework, sensing technologies are concerned with the detection and tracking of static and dynamic airborne objects that can initiate a potential collision threat. Furthermore, conflict detection can be thought of as the process of deciding when an action should be taken, and conflict resolution determines how or what action should be performed [31].

通常，CA 的基本功能是相似的，尽管不同方法的特定模型和警报阈值有所不同。一个明确基本 CA 功能的框架被用来分类 CA 方法。在这个框架中，感知技术涉及检测和跟踪可能引发碰撞威胁的静态和动态空中目标。此外，冲突检测可以被视为决定何时采取行动的过程，而冲突解决则确定如何或采取什么行动 [31]。

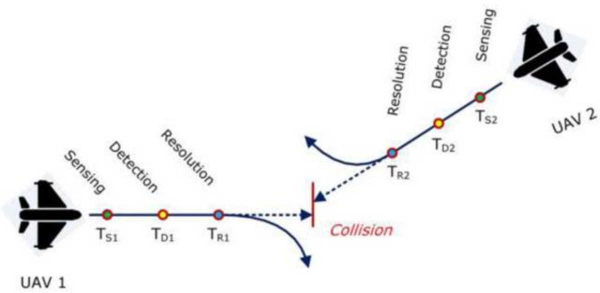

Fig. 3. CA process of UAVs.
图 3. 无人机的 CA 过程。

A.CA Process

A.CA 过程

Different CA approaches might emphasize different components or different sections of these components. However, a complete CA paradigm generally consists of sensing technologies, conflict detection, conflict resolution, and some related hardware [32]. A conceptual model of the common CA process is shown in Fig. 3 [24]. Information corresponding to UAVs and intruders is gathered by the installed sensing devices, which provide information on current flight-state scenarios. Based on the sensed status data, conflict detection is used to predict threats that may occur in the future and communicate with flight control to relay information on the detected threats. As the intruder approaches, conflict resolution provides strategies for threat resolution. This layer tries to find an optimal or feasible path under the constraints of UAV dynamics and fuel economics to avoid collisions. In reality, better UAV dynamics will have more and better conflict-resolution strategy options.

不同的碰撞避免 (CA) 方法可能会强调不同的组件或这些组件的不同部分。然而，一个完整的 CA 范例通常包括感知技术、冲突检测、冲突解决以及一些相关硬件 [32]。图 3[24] 展示了一个常见的 CA 过程的概念模型。无人机 (UAV) 和入侵者的信息由安装的感知设备收集，这些设备提供了当前飞行状态场景的信息。基于感知的状态数据，冲突检测用于预测未来可能发生的威胁，并与飞行控制通信，传递检测到的威胁信息。随着入侵者的接近，冲突解决提供了威胁解决的策略。这一层试图在无人机动态和燃油经济性的约束下找到最优或可行的路径以避免碰撞。实际上，更好的无人机动态将拥有更多和更好的冲突解决策略选项。

Note that individual functions in the CA process require specific time blocks. Considering UAV1 as an example, T_{S1} , T_{D1} , and T_{R1} denote the start of execution time needed by state sensing, conflict detection, and conflict resolution, respectively. Thus, CA can be considered a time-critical mission, and collision cannot be prevented if the total CA time exceeds the allowed time threshold.

注意，CA 过程中的单个功能需要特定的时间段。以 UAV1 为例，T_{S1} 、T_{D1} 和 T_{R1} 分别表示状态感知、冲突检测和冲突解决所需的执行时间起点。因此，CA 可以被视为一个时间关键任务，如果总的 CA 时间超过了允许的时间阈值，则无法防止碰撞。

The workflow of CA logic functions is illustrated in Fig. 4. Using the location and heading direction of nearby UAVs that are provided to the CA by the surveillance subprocedure, CA logic initiates and maintains a track on each UAV. For its own UAV and other UAVs involved in the same scenario, CA logic uses track information for continuously determining the current distance and time to the closest point of approach. State information is projected into the near future. If the predefined criteria associated with the current flight level are met, the intruder UAV is declared a threat. Depending on the evolving situation, the conflict-resolution function may be delayed or not selected at all. When the situation deteriorates, a decision is finally made whether an actual risk of conflict exists and if an avoidance maneuver is required. When an intruder UAV is declared a threat, the subsequent process involves encounter resolution by determining how and which maneuvers should be performed. Of course, other constraints should also be considered, such as aircraft performance and flight rules in a specific situation. Once the collision risk is addressed effectively, the involved UAVs return to their previously assigned routes.

CA 逻辑函数的工作流程在图 4 中有所说明。利用监视子程序提供给 CA 的附近无人机的位置和朝向信息，CA 逻辑对每个无人机进行跟踪并维持跟踪。对于其自身的无人机和参与同一场景的其他无人机，CA 逻辑使用跟踪信息来连续确定到最近接近点的当前距离和时间。状态信息被投影到不久的将来。如果与当前飞行级别相关的预设标准得到满足，入侵的无人机被宣布为威胁。根据情况的发展，冲突解决功能可能会延迟或者根本不被选择。当情况恶化时，最终会决定是否存在实际冲突风险以及是否需要进行避障机动。当入侵的无人机被宣布为威胁时，后续过程涉及确定如何以及哪些机动应该被执行的遭遇解决。当然，还应该考虑其他约束，例如特定情况下的飞机性能和飞行规则。一旦有效解决碰撞风险，涉及的无人机返回到之前分配的航线上。

The following discussion on these functions is intended to provide a general understanding of the process. The development of an effective CA system involves numerous special conditions and these are dependent on encounter geometry, range and altitude thresholds, and aircraft performance.

下面关于这些功能的讨论旨在提供对该过程的一般理解。开发一个有效的 CA 系统涉及许多特殊条件，这些条件取决于遭遇几何形状、距离和高度阈值以及飞机性能。

B. State Sensing

B. 状态感知

The state-sensing function enables the acquisition of status information on the surrounding environment, such as aircraft position, velocity, heading, and the number of intruders. This is realized using active/passive sensors and communication data links [33]. Traffic sensors can be mainly divided into cooperative and non-cooperative categories. Several types of sensors and sensing methods are employed in different CA approaches, with the most common being automatic-dependent surveillance broadcast (ADS-B), visual sensors, radars, cooperative UAVs information sharing, and assumed working sensors [34], [35]. The state information can be used to characterize the current traffic situation; it constitutes of several single and composite state parameters, such as the speed vector v , acceleration a , pitch angle φ , yaw angle ψ , rolling angle γ , and location vector $(x, y$, h).

状态感知功能使得获取周围环境的状态信息成为可能，例如飞机的位置、速度、航向以及入侵者的数

量。这是通过使用主动/被动传感器和通信数据链路 [33] 实现的。交通传感器主要可以分为合作和非合作两大类。在不同的冲突避免 (CA) 方法中使用了多种传感器和感知方法，最常见的是自动依赖监视广播 (ADS-B)、视觉传感器、雷达、合作无人机信息共享和假定工作传感器 [34]、[35]。状态信息可以用来描述当前交通情况；它包括多个单一和组合状态参数，如速度向量 v 、加速度 a 、俯仰角 φ 、偏航角 ψ 、滚转角 γ 和位置向量 (x, y ，h)。

C. Conflict Detection

C. 冲突检测

The conflict-detection function senses state data, extracts useful information, and discovers the risks of encounter. The states are dynamically calculated into the future to check whether a potential conflict will occur. It also picks up the relevant collision parameters for subsequent conflict resolution in case a potential threat is detected.

冲突检测功能感知状态数据，提取有用信息，并发现遭遇风险。状态会动态地计算到未来，以检查是否会发生潜在的冲突。如果检测到潜在威胁，它还会收集相关的碰撞参数以备后续冲突解决使用。

It is commonly accepted that a continuous system can be described using a discrete representation, and a discrete system can be described using a continuous model [36]. Generally, state variables only change at a certain instant or over a sequence of instances (discrete set of points in time), which are known as ”events” and remain constant in between events [37]. The flying UAVs incessantly survey for nearby aircraft and range and altitude tests are performed at regular intervals for each related target. Once a closing UAV meets or exceeds the corresponding criteria, it must be declared an intruder.

普遍认为，连续系统可以用离散表示来描述，离散系统也可以用连续模型来描述 [36]。通常，状态变量仅在特定瞬间或一系列瞬间 (时间点上的离散集合) 发生变化，这些被称为“事件”，在事件之间保持不变 [37]。飞行中的无人机不断地监测附近的飞机，并对每个相关目标定期进行距离和高度测试。一旦接近的无人机达到或超过相应的标准，它必须被宣布为入侵者。

D. Conflict Resolution

D. 冲突解决

The conflict-resolution function can identify deteriorating situations and generate effective maneuvers to resolve detected conflicts. Three fundamental control maneuvers can be used (either alone or in combination) to avoid a conflict: turn (horizontal/heading control maneuvers), climb/descent (vertical/altitude control maneuvers), and acceleration/deceleration (speed control maneuvers) [38]. Depending on the utilized CA approach, maneuvers may be carried out individually or in combination. Note that the combined maneuvers can be performed simultaneously or in sequence. Initiating a resolution maneuver needs at least one UAV to amend its original flight trajectory. For example, if two UAVs meet head-on at the same height, a turning strategy can be adopted; if two UAVs meet head-on at different heights, the higher UAV can climb and the lower drone can descend; if two UAVs on the same flight path are gradually approaching, the UAV in the front can accelerate and the UAV in the back can decelerate.

冲突解决功能能够识别恶化的情况并生成有效的机动动作来解决检测到的冲突。可以使用三种基本的控制机动 (单独或组合使用) 来避免冲突: 转向 (水平/航向控制机动)、爬升/下降 (垂直/高度控制机动) 以及加速/减速 (速度控制机动)[38]。根据所使用的冲突避免 (CA) 方法，机动可以单独执行或组合执行。注意，组合机动可以同时执行或按顺序执行。启动解决机动至少需要一架无人机修改其原始飞行轨迹。例如，如果两架无人机在相同高度迎头相遇，可以采用转向策略；如果两架无人机在迎头相遇但高度不同，较高无人机可以爬升而较低无人机可以下降；如果两架无人机在相同航迹上逐渐接近，前方无人机可以加速而后方无人机可以减速。

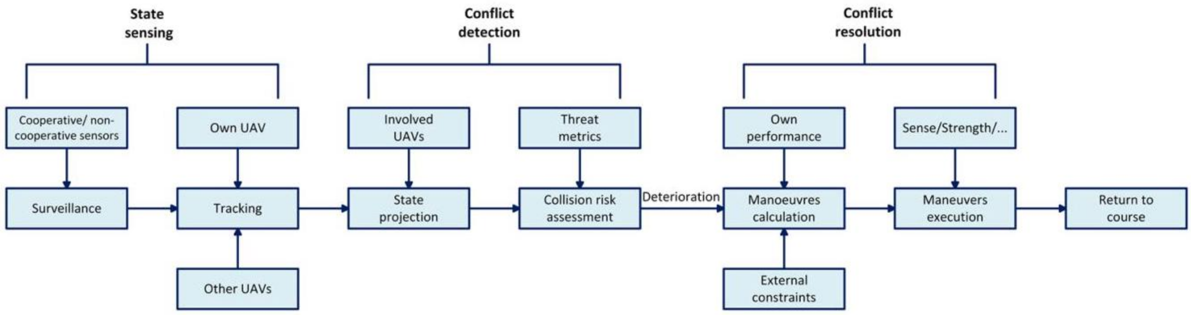

Fig. 4. Overview of the CA logic functions.
图 4。冲突避免逻辑功能概述。

Considering the scenario of multiple cooperative UAVs, many algorithms and methods, such as the ant colony algorithm, dynamic programming, genetic algorithm (GA), particle swarm optimization, potential field (PF), and their combinations and optimizations, have been proposed [39]. Furthermore, depending on the geometry of the realistic encounter, conflict resolution may be delayed or not selected at all, and any invalidated threat should be automatically filtered to improve calculation efficiency [40].

考虑到多个协作无人机的场景，已经提出了许多算法和方法，如蚁群算法、动态规划、遗传算法 (GA)、粒子群优化、势场 (PF) 以及它们的组合和优化 [39]。此外，根据实际遭遇的几何形状，冲突解决可能会延迟或根本不被选择，任何无效的威胁应该被自动过滤以提高计算效率 [40]。

III. SURVEY OF STATE SENSING

III. 状态感知调查

With the increasing use of UAVs, the problem of CA has become an important aspect of aviation safety [41]. The CA process for UAVs [42]-[44] can be approximately divided into three processes-real-time perceptual detection of its own flight status and the surrounding environment, analysis of the obtained data to detect potential collision risks, and redoing path planning to achieve conflict resolution. The first step of perceptual detection can be achieved using a wide variety of sensors. Sensing technology is fundamental for ensuring aviation safety. In this section, the existing sensing technologies for UAVs will be summarized. These technologies can be divided based on different standards into ground-based and air-based or cooperation and non-cooperation systems. These different sensors can be applied to specific aircraft, such as fixed-wing UAVs, rotorcraft, or those with different velocities, but can also be applied to other types of aircraft through improvements.

随着无人机使用的增加，碰撞避免 (CA) 问题已经成为航空安全的重要方面 [41]。无人机碰撞避免过程 [42]-[44] 可以大致分为三个步骤——实时感知检测自身的飞行状态和周围环境，分析获得的数据以检测潜在的碰撞风险，以及重新进行路径规划以实现冲突解决。感知检测的第一步可以通过各种传感器来实现。感知技术对于确保航空安全至关重要。在本节中，将对现有无人机的感知技术进行总结。这些技术可以根据不同的标准分为地面感知和空中感知，或者合作与非合作系统。这些不同的传感器可以应用于特定类型的航空器，如固定翼无人机、旋翼机或速度不同的无人机，也可以通过改进应用于其他类型的航空器。

A. Ground-Based and Air-Based Sensing Technology

A. 地面与空中感知技术

Depending on their location, sensors can be divided into ground-based and air-based sensors. Ground-based sensing technology refers to the use of air-traffic monitoring equipment and technologies on the ground to sense UAV flying space effectively, thereby arriving at situation analysis and averting collision risks, e.g., Video, Infrared, Lidar, and so on [45]. The air-based sensing technology refers to the use of airborne sensors and includes data links to achieve effective sensing, threat analysis, path planning, and maneuvering control of flight airspace, e.g., EO, TCAS, ADS-B, and so on [42]. The advantage of ground-based sensing technology is that it is mature and can result in highly accurate sensing in local areas. Its disadvantages include limited coverage, and in addition, the detection and perception of low-altitude small targets are easily affected by the environment [46], [47]. Air-based sensing technology does not rely on ground information support and can complete the sensing detection independently, which is considered the inevitable trend of autonomous and intelligent development of UAVs.

根据位置的不同，传感器可以分为地面传感器和空中传感器。地面传感技术指的是在地面上使用空中交通监控设备和技术在无人机飞行空间进行有效感知，从而进行情况分析和避免碰撞风险，例如视频、红外、激光雷达等 [45]。空中传感技术指的是使用机载传感器，并包括数据链路来实现有效感知、威胁分析、路径规划和飞行空域的机动控制，例如 EO、TCAS、ADS-B 等 [42]。地面传感技术的优点是技术成熟，可以在局部区域实现高度精确的感知。其缺点包括覆盖范围有限，此外，对低空小目标的探测和感知容易受到环境的影响 [46]，[47]。空中传感技术不依赖于地面信息支持，可以独立完成感知检测，被认为是无人机自主和智能发展的必然趋势。

B. Cooperative and Non-Cooperative Sensing

B. 合作与非合作感知

Sensors can be designated as cooperative and non-cooperative systems depending on the data exchange between a UAV and a target [48]. Cooperative sensing requires UAVs to be equipped with detection devices similar to those on the target. This technology mainly includes TCAS and ADS-B systems. TCAS [27], [49] systems are widely employed for civil aviation. A transponder is used in TCAS to transmit information during the detection process. ADS-B has built-in satellite positioning and uses broadcasts to transmit information, such as UAV position and speed [50]. Unlike TCAS, ADS-B uses satellite positioning, and hence, the transmitted data are relatively more accurate, but at the same time, it also requires expensive equipment.

根据无人机与目标之间的数据交换，传感器可以被指定为合作和非合作系统 [48]。合作感知要求无人机配备与目标上相似的检测设备。这项技术主要包括 TCAS 和 ADS-B 系统。TCAS [27]，[49] 系统在民用航空中得到了广泛应用。TCAS 在检测过程中使用应答机来传输信息。ADS-B 具有内置卫星定位，并通过广播传输信息，如无人机的位置和速度 [50]。与 TCAS 不同，ADS-B 使用卫星定位，因此传输的数据相对更准确，但同时也需要昂贵的设备。

Non-cooperative technologies do not require the target to have specific equipment, and hence, they are more versatile. Common non-cooperative sensors include video/electrooptic/infrared sensors and radar. In aerial imaging, flight airspace is relatively wide and the distance between the target and video sensor is large. This distance changes in real time, and hence, it is difficult to calculate most object features, which requires high-performance on-board computers [51]. Electro-optic sensors mainly detect targets by converting optical signals into electrical signals and are being used in fighter aircraft [52]. Electro-optic and video sensors are both based on natural light, owing to which they are easily affected by uncertain weather conditions. Infrared sensors, a subtype of electro-optic sensors, are good at detecting objects based on their temperature [53]. A synthetic aperture radar (SAR) is a high-resolution imaging radar that delivers high optical resolution radar images even in weather conditions with extremely low visibility [54]. Other sensors include sonar [55], Lidar [56], and other systems.

非合作技术不需要目标具备特定设备，因此它们更具通用性。常见的非合作传感器包括视频/电光/红外传感器和雷达。在航空成像中，飞行空域相对较宽，目标与视频传感器之间的距离较大。这个距离会实时变化，因此难以计算大多数物体特征，这需要高性能的机载计算机 [51]。电光传感器主要通过将光信号转换为电信号来探测目标，并且正在战斗机中使用 [52]。电光和视频传感器都是基于自然光，因此它们容易受到不确定天气条件的影响。红外传感器是电光传感器的一个子类型，擅长基于物体的温度来探测目标 [53]。合成孔径雷达 (SAR) 是一种高分辨率成像雷达，即使在能见度极低的天气条件下也能提供高光学分辨率的雷达图像 [54]。其他传感器包括声纳 [55]、激光雷达 [56] 等系统。

TABLE I

COMPARISON OF THE PERFORMANCE OF VARIOUS SENSORS

各种传感器性能比较

Sensor	Non-cooperative target detection	Detection range (km)	Non-visible environment	Calculation requirements	Cost
Video	✓	3	×	High	Low
EO	✓	20	×	Low	Low
Infrared	✓	5	✓	Low	Low
SAR	✓	35	✓	Low	Low
Sonar	✓	10	✓	Low	Low
Lidar	✓	3	✓	Low	High
TCAS	✓	160	✓	High	High
ADS-B	✓	240	✓	High	Low

传感器	非合作目标检测	检测范围 (公里)	非可视环境	计算要求	成本
视频	✓	3	×	高	低
电光	✓	20	×	低	低
红外	✓	5	✓	低	低
合成孔径雷达	✓	35	✓	低	低
声纳	✓	10	✓	低	低
激光雷达	✓	3	✓	低	高
空中交通防撞系统	✓	160	✓	高	高
广播式自动相关监视	✓	240	✓	高	低

TABLE II
SUMMARY OF THE LITERATURE ON CONFLICT-DETECTION METHODOLOGIES
冲突检测方法文献综述

Publication	Certain(C)/ uncertain(U)	Individual(I)/ Formation(F)	Position concerned	Time concerned	Fixed altitude	Cooperative	Obstacles concerned
Ruiz et al. [60]	C	I	✓	✓			
Yang et al. [61]	C	F	✓		✓		
Asmar et al. [62]	C	I	✓				
Tamás et al. [63]	C	I	✓				✓
Tang et al. [25]	C	F			✓	✓	
Thompson et al. [66]	C	F				✓	
Gageik et al. [67]	C	I				✓	✓
Kanno et al. [68]	C	F				✓	
Kang and Landry [69]	C	F					
Prandini et al. [70]	U	F	✓	✓	✓		
Albaker and Rahim [71]	U	I	✓	✓		✓	
Ho et al. [72]	U	F	✓	✓			
Park et al. [73]	U	F	✓	✓			
Corné et al. [74]	U	I	✓	✓			
Yang et al. [75]	U	F	✓	✓			
Yang et al. [76]	U	F	✓			✓	
Hu et al. [77]	U	I	✓			✓	
Liu et al. [78]	U	I	✓				
Lin et al. [79]	U	F		✓		✓	
Alejo et al. [80]	U	F			✓	✓	

出版物	确定 (C)/不确定 (U)	个体 (I)/编队 (F)	位置相关	时间相关	固定高度	协作	障碍物相关
Ruiz 等人 [60]	C	I	✓	✓			
杨等人 [61]	C	F	✓		✓		
Asmar 等人 [62]	C	I	✓				
Tamás 等人 [63]	C	I	✓				✓
唐等人 [25]	C	F			✓	✓	
Thompson 等人 [66]	C	F				✓	
Gageik 等人 [67]	C	I				✓	✓
Kanno 等人 [68]	C	F				✓	
Kang 和 Landry[69]	C	F					
Prandini 等人 [70]	U	F	✓	✓	✓		
Albaker 和 Rahim[71]	U	I	✓	✓		✓	
Ho 等人 [72]	U	F	✓	✓			
Park 等人 [73]	U	F	✓	✓			
Corné 等人 [74]	U	I	✓	✓			
杨等人 [75]	U	F	✓	✓			
杨等人 [76]	U	F	✓			✓	
Hu 等人 [77]	U	I	✓			✓	
Liu 等人 [78]	U	I	✓				
Lin 等人 [79]	U	F		✓		✓	
Alejo 等人 [80]	U	F			✓	✓	

The performance of various sensors is compared in Table I.
表 I 中比较了各种传感器的性能。

Any kind of single sensing technology has its own best application scenario and certain shortcomings. In addition, the actual airspace environment is very complicated, the targets might be cooperative or non-cooperative, and their shapes and speeds are also different. Therefore, multiple sensors of different types are necessary for multisource information fusion and detection. Fasano et al. [57] proposed a fully autonomous UAV CA system incorporating optical and radar sensors and discussed information fusion target detection, multisource-integrated decision making, and maneuver control. Through the comprehensive use of UAV photogrammetry and airborne lidar, specific objects can be detected more effectively [58]. Wilson et al. [59] investigated the coupling of two different types of real-time sensors. In general, the structure, data processing, and transmission of a perceptual detection system based on multisource information fusion are complex; moreover, there are various application obstacles (including those regarding software and hardware) that should be resolved.

任何一种单一感知技术都有其最佳应用场景和一定的不足。此外，实际的空域环境非常复杂，目标可能是合作的或非合作的，它们的形状和速度也有所不同。因此，为了多源信息融合和检测，需要多种不同类型的传感器。Fasano 等人 [57] 提出了一种完全自主的无人机 (UAV) 协同作业 (CA) 系统，该系统整合了光学和雷达传感器，并讨论了信息融合目标检测、多源集成决策和机动控制。通过综合使用无人机摄影测量和机载激光雷达，可以更有效地检测特定目标 [58]。Wilson 等人 [59] 研究了两种不同类型实时传感器的耦合。总的来说，基于多源信息融合的感知检测系统的结构、数据处理和传输是复杂的；此外，还存在各种应用障碍 (包括软硬件方面的问题) 需要解决。

As to the calculation requirements and costs in Table I, we do not provide specific magnitudes instead of "high" and "low" because this is a relative concept relative to the situation between the various sensors. A certain sensor is used in different aircraft and situations, and the values of "calculation requirements" and "cost" will be different.

关于表 I 中的计算要求和成本，我们没有提供具体的量级，而是用“高”和“低”这样的相对概念，因为这是相对于不同传感器之间的情况而言的。某种传感器在不同的飞机和情况下使用，其“计算要求”和“成本”的值将有所不同。

IV. SURVEY OF CONFLICT DETECTION

IV. 冲突检测概述

A conflict is defined as a scenario in which different aircraft may pose threats to each other. There are various conflict-detection methodologies based on different characteristics, such as certainty, position concerned, time concerned, fixed altitude, cooperative characteristics, and obstacles. A summary of the literature available on conflict-detection methodologies is presented in Table II. Conflict detection can be categorized into two types: considering certainty and not considering certainty. And these conflict-detection approaches could be applicable to the individual UAVs or UAV formation. "Certain" indicates that the method did not consider uncertainty, while "uncertain" indicates that the method considered uncertainty alone. "Position concerned" indicates that the method considered the position of each agent. "Time considered" indicates that the method takes the time criterion into consideration. "Fixed altitude" indicates that the method can only be applied to two-dimensional (2-D) circumstances. "Cooperative" means that the method can support message exchange between the agents. "Obstacle concerned" means that the method considered static obstacles in addition to dynamic UAVs.

冲突定义为不同飞行器可能对彼此构成威胁的场景。基于不同的特性，如确定性、相关位置、相关时间、固定高度、协作特性以及障碍物，存在多种冲突检测方法。关于冲突检测方法的文献总结在表 II 中呈现。冲突检测可以分为两种类型: 考虑确定性和不考虑确定性。这些冲突检测方法可能适用于单个无人机或无人机编队。" 确定" 表示该方法未考虑不确定性，而" 不确定" 表示该方法仅考虑了不确定性。" 相关位置" 表示该方法考虑了每个代理的位置。" 考虑时间" 表示该方法将时间标准纳入考虑。" 固定高度" 表示该方法仅适用于二维 (2-D) 情况。" 协作" 意味着该方法可以支持代理之间的消息交换。" 考虑障碍物" 表示该方法除了考虑动态无人机外，还考虑了静态障碍物。

A. Conflict Detection With Certainty

A. 确定性冲突检测

Conflict-detection methods can be mainly divided into "position-concerned" and "position not concerned" categories. The former accomplishes conflict detection by focusing on the relative position of different agents, while the latter focuses on the logic of conflict-detection procedures.

冲突检测方法主要可以分为" 考虑位置" 和" 不考虑位置" 两大类。前者通过关注不同代理的相对位置来完成冲突检测，而后者则专注于冲突检测程序的逻辑。

The position-concerned method mostly relies on data gathering and processing. Spatial data structures (SDSs) are the databases that can store position information. An SDS requires only the aircraft identity document (ID) and time window for the corresponding aircraft. The conflict detection uses a simplified wake vortex modeling through 4-D tubes to detect time-based separation infringements. [60]. Apart from position information, the distribution of different agents also plays an important role. Airspace is divided into different levels in civil aviation. Detection rules are based on the definition of the safe region and discussed in two dimensions for a certain level. UAV safe regions are usually defined in a 3-D space. Because traffic can be congested, potential conflicts should be considered and can be treated as maneuver constraints for relevant agents [61]. When it comes to information exchange between agents, aircraft transponders can provide altitude information for air-traffic control separation services. However, a quantization of 100 ft makes rate estimation very difficult. Trackers embedded in TCAS can produce single-point estimates of the vertical rate. Their accuracy can be improved by considering state uncertainty. A decision-theoretic approach can accommodate state uncertainty as a probability distribution. The Kalman filter, which can be integrated into next-generation (NextGen) TCAS logic, exhibits good performance for quantized measurements [62]. In detecting conflict with static obstacles, visual detection technology plays an important role; this technology can make use of low-cost airborne video capture equipment; in addition, visual detection methods can satisfy the strict size, weight, power, and cost constraints. Topographic operators should be defined so that the detection algorithm can efficiently be solved on cellular processor arrays [63]. Besides, Zarándy et al. [64] implemented a UAVs collision warning algorithm on cellular sensors and achieved great results. Yasin et al. [65] conducted a comprehensive analysis of these sensors and CA used in UAV visual inspection.

位置相关方法主要依赖于数据收集和处理。空间数据结构 (SDSs) 是能够存储位置信息的数据库。SDS 仅需要相应飞机的身份文档 (ID) 和时间窗口。冲突检测通过 4-D 管道简化尾涡模型来检测基于时间的间隔违规。[60] 除了位置信息，不同代理的分布也扮演着重要角色。在民用航空中，空域被划分为不同的层级。检测规则基于安全区域的定义，并在某一特定层级的两个维度进行讨论。无人机安全区域通常在三维空间中定义。由于交通可能会拥堵，潜在的冲突应当被考虑，并可以作为相关代理的机动约束 [61]。在代理之间的信息交换方面，飞机应答器可以为空中交通管制分离服务提供高度信息。然而，100 英尺的量化使得速率估计变得非常困难。嵌入在 TCAS 中的跟踪器可以产生垂直速率的单点估计值。通过考虑状态不确定性，可以提高其准确性。决策理论方法可以将状态不确定性作为一个概率分布来接纳。卡尔曼滤波器可以集成到下一代 (NextGen)TCAS 逻辑中，对于量化测量表现出良好的性能 [62]。在检测与静态障碍物的冲突中，视觉检测技术发挥着重要作用；这项技术可以利用低成本机载视频捕获设备；此外，视觉检测方法可以满足严格的大小、重量、功率和成本限制。地形运算符应当被定义，以便检测算法可以在单元处理器阵列上高效地解决 [63]。此外，Zarándy 等人 [64] 在单元传感器上实现了无人机碰撞警告算法，并取得了很好的结果。Yasin 等人 [65] 对这些传感器以及无人机视觉检查中使用的 CA 进行了全面分析。

Position and speed vectors are mainly used when the lack of uncertainty is assumed, and the logic process of conflict plays an important role. Further work should be carried out to predict potential conflicts caused by uncertainty. The cause-effect relationship of each action can be used to find out potential conflicts and, thus, can aid pilots in making cooperative and optimal maneuvers [25]. Furthermore, conflict detection is amenable to parallel processing due to its computationally intensive nature. Streams of asynchronous programming and applied multiple GPUs can improve the performance of conflict-detection algorithms [66]. The required equipment is affordable and detection quality can be improved using the data-fusion method. Conflict detection can be realized using low-cost ultrasonic and infrared range finders, which are much cheaper but noisier than sensors, such as laser scanners. To obtain the best possible result from multiple sensors, a weighted filter, which uses the concept of data fusion or data selection, can be applied [67]. To detect conflicts precisely, a conflict should be defined as a set of individual intentions and false beliefs (undesired procedures) and detection should be carried out for such combinations [68]. Scan-path training has been found to be effective for reducing the number of false alarms produced by novices after a short training period with no substantial reduction in separation-detection performance [69].

位置和速度矢量主要用于假设不存在不确定性的情况下，冲突的逻辑处理过程起着重要作用。应进一步开展研究，以预测不确定性引起的潜在冲突。可以通过分析每个行动的因果关系来发现潜在的冲突，从而帮助飞行员进行合作和最优的机动 [25]。此外，由于冲突检测的计算密集型特性，它适用于并行处理。异步编程流和应用多 GPU 可以提高冲突检测算法的性能 [66]。所需的设备价格合理，可以通过数据融合方法提高检测质量。可以使用低成本超声波和红外测距仪实现冲突检测，这些设备比激光扫描仪等传感器便宜但噪声大。为了从多个传感器中获得最佳结果，可以应用加权滤波器，该滤波器使用数据融合或数据选择的概念 [67]。为了精确检测冲突，应将冲突定义为一系列个别意图和错误信念 (不希望的程序) 的集合，并应对这些组合进行检测 [68]。扫描路径训练被发现对减少初学者在短期训练后产生的误报数量有效，且不会实质性降低分离检测性能 [69]。

B. Conflict Detection Without Certainty

B. 不确定条件下的冲突检测

In the case of conflict detection without certainty, this method takes the uncertainty factor into consideration. The method discussed below considers all probabilistic scenarios and suggests various tactics to meet threats in different circumstances.

在不确定条件下进行冲突检测时，该方法考虑了不确定性因素。下面讨论的方法考虑了所有概率场景，并提出了在不同情况下应对威胁的各种策略。

The positions of different agents are important in conflict detection without certainty. Probabilistic models for predicting aircraft position in the near- and midterm future can provide a measure of criticality for an encounter between two aircraft, which is called the maximum instantaneous probability of conflict. Randomized algorithms can efficiently estimate this measure of criticality and provide quantitative bounds for the level of approximation introduced [70]. However, this method cannot satisfy cooperative circumstances. Conflict detection can be realized by analyzing the flight-plan segments of conflicting aircraft to extract collision parameters, which include collision point, time to collision, collision interval, and collision angle. Potential conflicts can be detected by cooperatively projecting the states of future flight trajectories of conflicting aircraft [71]. The actual body radius of each aircraft can be enlarged by adding extra layers to guarantee safety. The body radius that represents different uncertainty margins and the minimum separation distance is determined as airspace constraints [72]. Simple geometric approaches can be used when aircraft are linked by the real-time system, such as ADS-B. This detection method mainly calculates the point of closest approach (PCA) to evaluate the worst conflict scenario [73]. In addition, the flow rate of conflict probability at the boundary of a conflict zone can be used to formulate the general probabilistic conflict-detection problem. A tight upper bound for the probability of conflict over a given time period can be calculated in real time using adaptive numerical integration [74]. To improve the efficiency of conflict detection in a large number of aircraft conditions, hierarchical asynchronous conflict detection, which is based on the data-update strategy, can be applied [75].

在不确定性的冲突检测中，不同代理的位置是重要的。预测飞机在近期和中期未来位置的概率模型可以为两架飞机相遇的临界性提供一个衡量标准，这被称为最大瞬时冲突概率。随机算法可以有效地估算这种临界性衡量标准，并为引入的近似程度提供定量界限 [70]。然而，这种方法无法满足合作情况。通过分析冲突飞机的飞行计划段来提取碰撞参数，可以实现冲突检测，这些参数包括碰撞点、碰撞时间、碰撞间隔和碰撞角。通过合作预测冲突飞机未来飞行轨迹的状态，可以检测潜在的冲突 [71]。可以通过添加额外层来增大每架飞机的实际半径，以保证安全。代表不同不确定性边缘和最小间隔距离的身体半径被确定为空域约束 [72]。当飞机通过实时系统 (如 ADS-B) 连接时，可以使用简单的几何方法。这种检测方法主要计算最近点 (PCA) 来评估最糟糕的冲突场景 [73]。此外，冲突区域边界的冲突概率流量可以用来构建一般概率冲突检测问题。在给定时间段内，使用自适应数值积分可以实时计算冲突概率的紧上界 [74]。为了在大量飞机条件下提高冲突检测的效率，可以应用基于数据更新策略的分层异步冲突检测 [75]。

Some predicting methods can be applied to improve conflict-forecast quality. Probabilistic reachability analysis has been proposed to take the uncertainty in aircraft future position into consideration. Conflicts are detected by calculating the ellipsoidal reach sets of different aircraft [76]. The probability of conflict can be estimated by introducing a Markov chain approximation of the stochastic process describing the relative position of an aircraft [77]. A probabilistic conflict-detection algorithm based on the 4-D trajectory prediction is an option for the NextGen air-transportation systems. A Gaussian random variable is used to represent the relative distance between two aircraft, while the tail probability of the quadratic form of Gaussian random variables is used to calculate conflict probability; this can be solved by saddle point approximation [78].

一些预测方法可以应用于提高冲突预测的质量。已经提出概率可达性分析来考虑飞机未来位置的不确定性。通过计算不同飞机的椭球型可达集来检测冲突 [76]。通过引入描述飞机相对位置的随机过程的马尔可夫链近似，可以估计冲突的概率 [77]。基于 4-D 轨迹预测的概率冲突检测算法是下一代航空运输系统的选择之一。使用高斯随机变量表示两架飞机之间的相对距离，同时使用高斯随机变量的二次形式的尾部概率来计算冲突概率；这可以通过鞍点近似法解决 [78]。

TABLE III

SUMMARY OF TYPICAL CONFLICT-RESOLUTION METHODOLOGIES

典型冲突解决方法的概述

Symbol	Individual		formation		Cooperative	Centralized (C /Distributed (D)
	Pair	Multiple	Inner conflict	Outer conflict		
Chakravarthy and Ghose [82]	3				✓	C
Goss et al. [83]	✓				×	C
Carbone et al. [84]	✓				×	C
Luongo et al. [85]	✓				×	C
Han and Bang [86]	✓				×	C
Sigurd and How [87]		✓			✓	C
Liu et al. [88]		✓			✓	C
Richards and How [89]		✓			✓	C
Alejo et al. [90]		✓			✓	C
Temizer et al. [91]		✓			✓	C
Wan et al. [92]		✓			✓	D
Zavlanos and Pappas [93]			✓		✓	D
Atınç et al. [94]			✓		✓	D
Paul et al. [95]			✓		✓	D
Richards and How [96]			✓		✓	D
Hafez et al. [97]			✓		✓	D
Ille and Namerikawa [98]			✓		✓	D
Vásárhelyi et al. [2]			✓	✓	✓	D
Wan et al. [99]			✓	✓	✓	D

符号	个体		形成过程		协作的	集中式 (C)/分布式 (D)
	成对	多个	内部冲突	外部冲突		
Chakravarthy 和 Ghose [82]	3				✓	C
Goss 等人 [83]	✓				×	C
Carbone 等人 [84]	✓				×	C
Luongo 等人 [85]	✓				×	C
Han 和 Bang [86]	✓				×	C
Sigurd 和 How [87]		✓			✓	C
Liu 等人 [88]		✓			✓	C
Richards 和 How [89]		✓			✓	C
Alejo 等人 [90]		✓			✓	C
Temizer 等人 [91]		✓			✓	C
Wan 等人 [92]		✓			✓	D
Zavlanos 和 Pappas[93]			✓		✓	D
Atınç 等人 [94]			✓		✓	D
Paul 等人 [95]			✓		✓	D
Richards 和 How[96]			✓		✓	D
Hafez 等人 [97]			✓		✓	D
Ille 和 Namerikawa[98]			✓		✓	D
Vásárhelyi 等人 [2]			✓	✓	✓	D
Wan 等人 [99]			✓	✓	✓	D

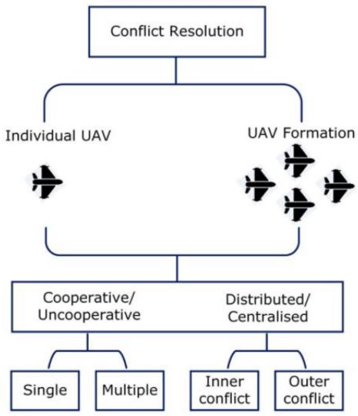

Fig. 5. Structure of conflict-resolution methodologies.
图 5. 冲突解决方法的结构。

Several conflict-detection methods are not position concerned. Time-division multiple access (TDMA) is a method for multiple aircraft to detect conflicts logically. TDMA is responsible for checking the designated time slots and reallocating conflict IDs. This mechanism can assist the transponder in effectively sharing data with multiple nearby aircraft [79]. A conflict-detection algorithm can be designed based on an axis-aligned minimum bounding box that does not rely on the exact position of agents. A security envelope around an aircraft can be used to avoid collisions and it may be approximated by horizontal and vertical boxes that cover the aerial robot [80].

有几种冲突检测方法与位置无关。时分多址 (TDMA) 是一种让多架飞机逻辑上检测冲突的方法。TDMA 负责检查指定的时隙并重新分配冲突 ID。这种机制可以帮助应答器有效地与多个附近飞机共享数据 [79]。可以设计一种基于轴对齐最小边界框的冲突检测算法，该算法不依赖于代理的确切位置。围绕飞机的安全包络可以用来避免碰撞，并且可以通过覆盖航空机器人的水平和垂直盒子来近似 [80]。

V. SURVEY OF CONFLICT RESOLUTION

V. 冲突解决的调查

Conflict resolution for UAVs refers to threat resolution between different agents and involves determining how and what measures should be taken when a collision is predicted [81]. As illustrated in Fig. 5, these methodologies can be divided into two types based on the algorithm functions for UAV individuals and formations. Conflict resolution for individual UAVs refers to paired UAVs and multiple UAVs. In the "pair" method, the conflict between two individual aircraft is resolved. In the "multiple" method, the conflict between multiple aircraft is resolved. Similarly, in the "formation" method, the conflict between UAV formations is resolved. Methods for conflict resolution in UAV formations refer to methods for inner conflict and outer conflict. The former refers to conflict resolution between UAVs in one formation, while the latter refers to conflicts between different formations. Table III summarizes the typical conflict-resolution methodologies currently known. Here, "cooperative" means that UAVs communicate and coordinate with each other when resolving conflicts. Furthermore, UAV conflict-resolution methodologies can be classified as centralized or distributed. The former assumes that the resolution strategy is calculated and selected by a centralized entity and conveyed to UAVs via a special-purpose long-range low-bit-rate radio interface. Meanwhile, in distributed approaches, UAVs work cooperatively to adjust their position based on local interactions to achieve an optimal strategy.

无人机冲突解决指的是不同代理之间的威胁解决，涉及在预测到碰撞时确定如何以及应该采取哪些措施 [81]。如图 5 所示，这些方法可以根据无人机个体和编队的算法功能分为两种类型。针对单个无人机的冲突解决指的是成对的无人机和多个无人机。在“成对”方法中，解决两个单独飞行器之间的冲突。在“多个”方法中，解决多个飞行器之间的冲突。同样，在“编队”方法中，解决无人机编队之间的冲突。无人机编队中的冲突解决方法指的是内部冲突和外部冲突的解决方法。前者指的是同一编队内无人机之间的冲突解决，而后者指的是不同编队之间的冲突。表 III 总结了当前已知的典型冲突解决方法。这里的“协同”意味着无人机在解决冲突时相互通信和协调。此外，无人机冲突解决方法可以根据是集中式还是分布式进行分类。前者假设解决策略是由集中实体计算和选择的，并通过专用长距离低比特率无线接口传达给无人机。同时，在分布式方法中，无人机通过本地交互合作调整位置以实现最优策略。

A. Individual UAVs

A. 单个无人机

There are two main conflict-resolution methods for individual UAVs: tactical and strategic. The former mainly refers to GA, which resolves conflicts by analyzing the relative geometry situation between a pair of UAVs and considers the dynamics of UAVs more. Chakravarthy and Ghose [82] proposed PCA, which predicts the time τ and minimum vector distance r_m of two UAVs to reach the closest position in space. Goss et al. [83] and Carbone et al. [84] proposed a collision cone approach, which could be summarized into two steps. In the first step, the algorithm builds an isolation area cantered at the intruder with a safe distance as the radius. In the second step, the local drone adjusts its relative speed to traverse tangentially with respect to the constructed sphere. In [31] and [85], this sphere was transformed into a cylindrical isolation area by adjusting the proportion of horizontal and vertical distances. Han et al. [86] dynamically adjusted the isolation area of a given UAV to fit different scenarios.

个体无人机主要有两种冲突解决方法: 战术性和战略性。前者主要指的是遗传算法 (GA)，它通过分析一对无人机之间的相对几何位置情况来解决冲突，并更多地考虑无人机的动态特性。Chakravarthy 和 Ghose [82] 提出了预测碰撞算法 (PCA)，该算法预测了两架无人机在空间中达到最近位置的时间 τ 和最小向量距离 r_m 。Goss 等人 [83] 和 Carbone 等人 [84] 提出了碰撞圆锥方法，可以概括为两个步骤。第

一步，算法构建一个以入侵者为圆心、安全距离为半径的隔离区域。第二步，局部无人机调整其相对速度，以切线方式穿越构建的球体。在 [31] 和 [85] 中，通过调整水平和垂直距离的比例，将这个球体转换为一个圆柱形隔离区域。Han 等人 [86] 动态调整给定无人机的隔离区域以适应不同场景。

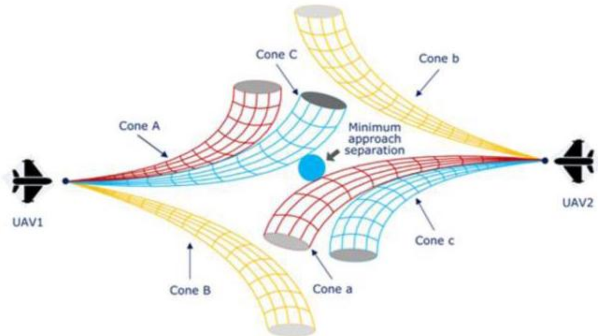

Fig. 6. Coordination between two UAVs.
图 6. 两个无人机之间的协调。

The latter pieces of literature mainly include the path-planning algorithm. By actively planning the collision-free path between two positions, the conflict-resolution problem is transformed into a path-planning problem with the constraint of a minimum safety interval. Collision-free path-planning methods include the PF [87], [88], linear programming [89], discretized space [90], and stochastic theory [91] methods. Among these, the PF method is the most common method. It constructs a compound PF to restrict flying UAVs in a limited airspace, which contains gravitational sources produced by targets and repulsive sources produced by invaders and threats. When there are obstacles near the target point, the repulsive force would be very large, and the gravitational force would be relatively small, making it difficult for the UAV to reach the target point. The advantage of the linear programming method is that when there is less information about the UAVs involved in the encounter, a relatively better strategy could still be generated, but the factors that may be considered are not comprehensive and the calculation results are too ideal. The discretized space method is computationally efficient and can quickly generate results, but resolutions may be suboptimal. The stochastic theory is flexible enough to accommodate a variety of sensor modalities, intruder behavior, and UAV dynamics, but it has higher requirements for parameter settings if it needs to generate optimization results.

后续的文献主要包含路径规划算法。通过积极规划两个位置之间的无碰撞路径，冲突解决问题被转化为具有最小安全间隔约束的路径规划问题。无碰撞路径规划方法包括 PF [87]、[88]、线性规划 [89]、离散空间 [90] 和随机理论 [91] 方法。在这些方法中，PF 方法是最常见的方法。它构建了一个复合 PF 来限制飞行无人机在有限的空域内，该空域包含由目标产生的引力源和由入侵者及威胁产生的斥力源。当目标点附近有障碍物时，斥力会非常大，而引力相对较小，使得无人机难以到达目标点。线性规划方法的优点在于，当涉及相遇的无人机信息较少时，仍然可以生成相对较好的策略，但考虑的因素可能不够全面，计算结果过于理想。离散空间方法计算效率高，可以快速生成结果，但分辨率可能不是最优的。随机理论足够灵活，能够适应各种传感器模态、入侵者行为和无人机动力学，但如果需要生成优化结果，对参数设置的要求较高。

Hence, a drone can move in the direction in which the potential energy of the resultant force is reduced and, thus, avoid collision [87]. To overcome any possible local minimum points, Liu et al. [88] combined the PF method with the Lyapunov stability theorem. The PF method has a small calculation load and exhibits high real-time performance but faces the disadvantages of poor stability and a local minimum that is difficult to overcome.

因此，无人机可以朝着合成力的势能减小的方向移动，从而避免碰撞 [87]。为了克服可能的局部最小点，刘等人 [88] 将 PF 方法与李雅普诺夫稳定性定理相结合。PF 方法计算负载小，表现出高实时性能，但存在稳定性差和难以克服的局部最小值的缺点。

A tactical-strategic mixed conflict-resolution algorithm has also been proposed for multiple UAVs [92]. As depicted in Fig. 6, each UAV selects three candidate strategies from a preset pool of strategies. The uncertainty of the trajectory is taken into account so that the predicted trajectory looks like a cone. The aircraft in conflict coordinate and determine the primary combination of strategies. When a collision is imminent, these UAVs activate primary strategies to resolve conflicts.

针对多无人机，还提出了一个战术-战略混合冲突解决算法 [92]。如图 6 所示，每架无人机从预设的策略池中选择三种候选策略。考虑了轨迹的不确定性，使得预测轨迹呈现出圆锥形状。冲突中的飞机协调并确定主要策略组合。当碰撞即将发生时，这些无人机激活主要策略来解决冲突。

B.UAV Formation

B. 无人机编队

Conflict resolution in UAV formations is usually integrated with a control algorithm to ensure an orderly and stable formation. The strategy developed should ensure safety between agents inside one formation and avoid collision with outer threats (other formations). This methodology includes rule-based, optimization-based, strategy-coordination-based, and swarm-intelligence-based methods.

无人机编队中的冲突解决通常与控制算法集成，以确保编队的有序和稳定。开发的策略应确保编队内各代理之间的安全，并避免与外部威胁 (其他编队) 发生碰撞。这种方法包括基于规则、基于优化、基于策略协调和基于群体智能的方法。

The artificial PF method is a popular example of rule-based methods [93], [94]. Here, the local PF is modified to realize formation conflict resolution. Paul et al. [95] proposed a method for flight formation and reconfiguration in which the local PF is modified to contain only a repulsion force to increase the distance between two approaching drones. In general, optimization-based methods used model predictive control to realize formation control with conflict resolution [96]-[98]. A method has been proposed for conflict resolution between multi-UAV formations by expanding the cost function and adding a penalty item [98].

人工势场方法是基于规则方法的典型例子 [93]、[94]。在这里，局部势场被修改以实现编队冲突解决。Paul 等人 [95] 提出了一种飞行编队和重构方法，其中局部势场被修改，仅包含排斥力以增加两架接近的无人机之间的距离。一般来说，基于优化的方法使用模型预测控制来实现带有冲突解决的编队控制 [96]-[98]。已经提出了一种通过扩展成本函数和添加惩罚项来解决多无人机编队之间冲突的方法 [98]。

Swarm-intelligence-based methods [2] resolve conflicts for swarms with a large number of drones by setting a series of basic interaction laws for individual drones in swarms; the decentralized law ensures a minimum safe distance for drones and the avoidance law prevents different swarms from getting too close to each other. Weight parameters are adjusted to achieve different conflict-resolution solutions. The conflict-resolution algorithm for UAV swarms mainly focuses on ensuring safety and order and preventing collision between UAVs inside a formation. Strategy-coordination-based methods are also employed for conflict resolution between UAV formations. Wan et al. [99] proposed a distributed conflict-resolution method for UAV formations to consider inner and outer conflicts simultaneously. Each swarm in conflict selects three candidate CA maneuvers and coordinates to determine the optimal combination of strategies.

基于群体智能的方法 [2] 通过为群体中的单个无人机设定一系列基本交互法则来解决大量无人机的冲突；去中心化法则确保了无人机之间的最小安全距离，而避让法则防止不同群体之间的无人机过于接近。通过调整权重参数来实现不同的冲突解决策略。无人机群体的冲突解决算法主要关注确保安全和秩序，防止编队内无人机之间的碰撞。基于策略协调的方法也用于解决无人机编队之间的冲突。万等 [99] 提出了一种分布式无人机编队冲突解决方法，同时考虑内部和外部冲突。每个冲突中的群体选择三种候选的冲突避免 (CA) 机动，并通过协调确定策略组合的最优方案。

In summary, there are different conflict-resolution methodologies, with each having its own advantages and disadvantages. The theory of conflict resolution for individual UAVs is very mature, but conflict resolution for UAV formations is far from being fully developed, especially for large-scale UAV clusters. In addition, some valuable research aimed at improving both the performance and the coverage area of UAVs based on the cooperation of different UAVs in a network [100]. Typically, Wang et al. [101] proposed a two-stage joint hovering altitude and power control solution for the resource allocation problem in UAV networks.

总结来说，存在不同的冲突解决方法，每种方法都有其自身的优缺点。针对单个无人机的冲突解决理论非常成熟，但无人机编队的冲突解决远未完全发展，尤其是对于大规模无人机集群。此外，还有一些有价值的研究致力于通过网络中不同无人机的合作来提高无人机的性能和覆盖区域 [100]。通常，王等 [101] 提出了一种两阶段联合悬停高度和功率控制解决方案，用于无人机网络中的资源分配问题。

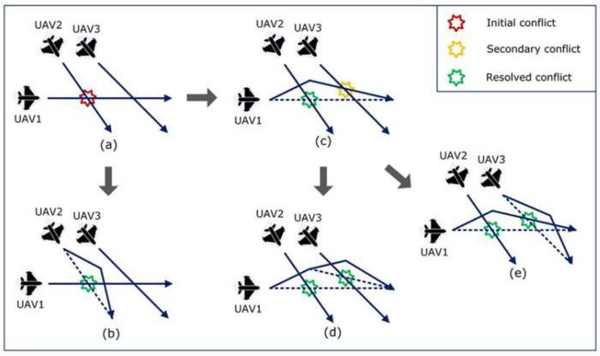

Fig. 7. Strategy selection for domino conflict.
图 7. 多米诺冲突的策略选择。

VI. TECHNOLOGICAL CHALLENGE

VI. 技术挑战

With the development of artificial intelligence, the use of machine learning methods, such as deep learning and reinforcement learning to avoid collisions with UAVs, is also an important direction [102], [103]. Singla et al. [104] proposed a deep reinforcement learning method using a recurrent neural network with temporal attention to automatically avoid UAVs collisions with obstacles in unstructured and unknown indoor environments. Dai et al. [105] applied a model based on the convolutional neural network to predict the probability of collision and issue control commands to achieve autonomous obstacle avoidance for UAVs in an unknown indoor environment. Yan et al. [106] used the deep reinforcement learning algorithm of the dueling double deep Q -networks to plan potentially threatening UAV path. Behjat et al. [107] utilized the method of supervised learning and neural network training classifiers to control the actions of UAVs to achieve the online CA of multiple UAVs.

随着人工智能的发展，使用机器学习方法，如深度学习和强化学习来避免与无人机 (UAVs) 的碰撞，也是一个重要的研究方向 [102], [103]。Singla 等人 [104] 提出了一种深度强化学习方法，使用带有时间注意力的循环神经网络自动避免无人机在非结构化和未知的室内环境中的障碍物碰撞。Dai 等人 [105] 应用了一种基于卷积神经网络的模型来预测碰撞概率并发出控制指令，以实现无人机在未知室内环境中的自主避障。Yan 等人 [106] 使用了双重深度 Q -网络算法的深度强化学习来规划潜在的威胁无人机路径。Behjat 等人 [107] 利用监督学习和神经网络训练分类器的方法来控制无人机的行为，以实现多无人机的在线碰撞避免 (CA)。

The fundamental reason for the application of different UAVs is to remove the pilot from the aircraft in order to realize several key operational benefits. Compared with humans, they may be operated within harmful environments, staying airborne for a longer period of time without inducing pilot fatigue, executing at considerably low cost and human resources and so on. Meanwhile, a number of technological, social, and regulatory barriers must be addressed to ensure that the full potential of UAV can be realized. For facilitating the development of CA approaches to promote the widespread use of UAVs with reliable and safe operations, the major challenges are analyzed as follows:

无人机应用的基本原因是将飞行员从飞机中移除，以实现几个关键的操作优势。与人类相比，它们可以在有害环境中运行，长时间停留在空中而不会引起飞行员疲劳，以相当低的成本和人力资源执行任务等。同时，必须解决一系列技术、社会和监管障碍，以确保无人机的全部潜力得以实现。为了促进碰撞避免 (CA) 方法的发展，以推动无人机的广泛使用和可靠安全的运行，主要挑战分析如下:

1) Because the NextGen that permits the change of flight paths without approval from a centralized route control would be implemented in the near future [108], it becomes necessary that the different CA approaches executed in manned aircraft and UAVs could be absolutely synergic and compatible during the flight.

1) 由于下一代航空系统 (NextGen) 允许在无需集中路线控制批准的情况下改变飞行路径将在不久的将来实施 [108]，因此，不同碰撞避免方法在有人驾驶飞机和无人机上执行时，在飞行过程中必须完全协同和兼容。

2) The increased airspace usage can induce a secondary threat as a result of the conflict resolution, which may issue an improper maneuver that resolves a one-on-one encounter with a first threat [29], as

shown in Fig. 7. For instance, the planned trajectory of UAV1 has a conflict with the planned trajectory of UAV2, which is adjacent to UAV3. If UAV1 climbs to amend its trajectory, it will initiate a new threat with UAV3. Research that explores such potential collision scenarios is required to enable ATM to avoid a domino conflict when many manned and unmanned aircraft exist in the same region of airspace. To select the optimal strategy, it is necessary to consider the potential interactions among neighboring trajectories with a global scope of a basic volume in which all aircraft communicate well and cooperate with each other.

2) 增加的空域使用可能导致由于冲突解决而产生的次生威胁，这可能会发出不适当的机动，以解决与第一个威胁的一对一遭遇 [29]，如图 7 所示。例如，UAV1 的计划轨迹与相邻的 UAV3 附近的 UAV2 的计划轨迹冲突。如果 UAV1 上升以修正其轨迹，它将与 UAV3 引发新的威胁。需要进行研究以探索此类潜在的碰撞场景，以使空中交通管理 (ATM) 能够在许多有人驾驶和无人驾驶飞机存在于同一空域区域时避免多米诺骨牌式的冲突。为了选择最佳策略，需要考虑相邻轨迹之间的潜在交互，以及所有飞机都能良好通信和协作的基本体积的全局范围。

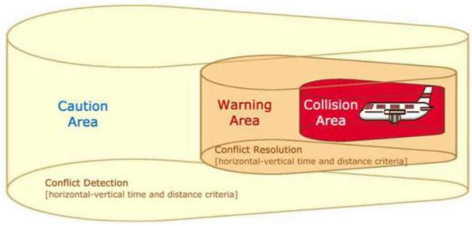

Fig. 8. Temporal-spatial synthesized protection volume of TCAS [109].

图 8。TCAS 的时空间合保护体积 [109]。

3) The unification of UAVs and the traditional aircraft in safety regulations are the basis for the integration of flight safety-related systems. For example, considering each TCAS-equipped aircraft, a temporal-spatial synthesized protection volume of airspace surrounds, as illustrated in Fig. 8 [109]. For the caution area and warning area, the horizontal time and distance criteria described above shape the horizontal boundaries of this volume, while the vertical time and distance thresholds determine the vertical dimensions of the protected volume. At present, UAVs generally adopt a single safety specification, temporal ”OR” spatial threshold, rather than ”AND.” In addition, it should be noted that the latest version of TCAS, called ACAS X, the future of airborne CA, has been tried to extend CA to other classes of aircraft, including UAVs

3) 无人机与传统飞行器在安全规定上的统一是飞行安全相关系统集成的基础。例如，考虑到每架配备 TCAS 的飞机，一个时空间合的保护体积围绕在空域周围，如图 8 所示 [109]。对于警告区域和谨慎区域，上述描述的水平时间和距离标准形成了该体积的水平边界，而垂直时间和距离阈值决定了保护体积的垂直尺寸。目前，无人机通常采用单一的安全规格，即时间的“或”空间阈值，而不是“和”。此外，应注意最新的 TCAS 版本，称为 ACAS X，即未来机载防撞系统 (CA)，已经尝试将 CA 扩展到包括无人机在内的其他类别的飞机。[110].

4) Excessive time delays in evaluating flight risks will lead to catastrophic events when not effectively accommodated; this is because rigorous CA is a time-critical mission [111]. In the future common airspace, at the phase of state sensing, conflict detection, conflict resolution, and other ATM tasks have been widely exploited in human operators (i.e., pilots and air-traffic controllers) for manned aircraft. Thus, in a scenario involving UAVs and manned aircraft, there are major challenges that need to be overcome to compensate for the negative effects of delays that involve great uncertainty.

4) 在评估飞行风险时，如果未能有效缓解过长的时延，将会导致灾难性事件；这是因为严格的冲突避免 (CA) 是一项对时间敏感的任务 [111]。在未来的通用空域中，在状态感知、冲突检测、冲突解决以及其他空中交通管理 (ATM) 任务的阶段，已经广泛利用了有人操作员 (即飞行员和空中交通管制员) 对有人驾驶飞机的操作。因此，在涉及无人机和有人驾驶飞机的场景中，需要克服重大挑战，以补偿涉及巨大不确定性的延迟带来的负面影响。

5) There are several other issues that are of critical importance to the operational application of CA approaches. The most typical issue is the hardware performance issue [112], which in terms of the ability of the automatic operators to respond appropriately and consistently to conflict alerts and finding an appropriate balance between false alarms and loss-of-separation incidents.

5) 在冲突避免方法操作应用中还存在着其他几个关键问题。最典型的问题是硬件性能问题 [112]，这涉及到自动操作员对冲突警报做出适当和一致反应的能力，以及在误报和失去间隔事件之间找到适当的平衡。

6) Choosing appropriate metrics to evaluate the performance of different CA approaches is difficult, as it should ensure that both safety and performance objectives are met. Especially, system efficiency is a vital evaluation index for ensuring that aircraft can follow directions or linear flight paths to their destinations [113]. CA approaches should meet safety criteria efficiently.

6) 选择适当的指标来评估不同冲突避免方法的性能是困难的，因为需要确保既满足安全目标，也满足性能目标。特别是，系统效率是确保飞机能够遵循指示或直线飞行路径到达目的地的重要评估指标 [113]。冲突避免方法应有效地满足安全标准。

7) UAV use in indoor environments is a challenging task; hence, CA in such scenarios is more difficult when compared with CA in outdoor environments [114]. This is because it is very difficult to use indoor positioning technology for avoiding collisions in a closed environment.

7) 在室内环境中使用无人机是一项具有挑战性的任务；因此，与室外环境相比，在这种场景下的冲突避免更为困难 [114]。这是因为室内定位技术在封闭环境中避免碰撞非常困难。

VII. CONCLUSION

VII. 结论

Due to their potential for application in both civilian and military fields, UAVs have attracted widespread attention. They can be remotely controlled or operated semiautonomously or autonomously at different cruise speeds, operating altitudes, endurances, and payloads. Separation assurance, which is at the core of aviation safety, is a multilayered process and CA capability is considered the last line of defense against the risk of collision. It is clear from the information presented in this review that there are a large number of approaches to the CA problem. Various aspects of CA approaches have been discussed as well as their advantages and disadvantages during threat resolution. It is our hope that this review presents researchers and system designers with a unique perspective on CA approaches for UAVs and provides a solid foundation for further research and development.

由于其在民用和军事领域应用的潜力，无人机 (UAVs) 已经引起了广泛关注。它们可以被远程控制，或者在不同的巡航速度、飞行高度、续航时间和载重下半自主或自主运行。分离保障是航空安全的核心，是一个多层次的过程，其中碰撞避免 (CA) 能力被认为是防止碰撞风险的最后一道防线。从本次综述中呈现的信息来看，解决 CA 问题有大量的方法。已经讨论了 CA 方法的各个方面以及它们在威胁解决过程中的优点和缺点。我们希望本次综述能为研究人员和系统设计人员提供关于无人机 CA 方法的独特视角，并为进一步的研究与发展奠定坚实基础。

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