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Integrating Unmanned Aerial Vehicles in Airspace: A Systematic Review

Arif TUNCAL[1] **Ufuk EROL**[2]

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Abstract

In this article, a comprehensive review of the integration of Unmanned Aerial Vehicles (UAVs) into shared airspace is presented. By applying a systematic review methodology, the study clarifies the main challenges, problems, and possible fixes related to safety, coordination, and regulatory frameworks. The results demonstrate the critical role that several elements play in supporting the safety of UAV integration. These elements include multi-layered airspace models, careful path planning, secure communication networks, Conflict Detection and Resolution (CDR) strategies, and strong regulations. The paper explores the potential of Human-in-the-loop Reinforcement Learning (HRL) and Reinforcement Learning (RL) algorithms to train UAVs for maneuvering through complex terrain and adapting to changing circumstances. The study's conclusions highlight the importance of ongoing research projects, stakeholder cooperation and continuous support for technology developments-all of which are necessary to ensure the safe and orderly integration of UAVs into airspace.

Key Words: Autonomous Vehicles; Artificial Intelligence; Reinforcement Learning; Unmanned Aerial Vehicle; Unmanned Traffic Management

JEL Classification: M10, L93, L94.

İnsansız Hava Araçlarının Hava Sahasına Entegrasyonu: Sistematik Bir İnceleme

Öz

Bu makalede, İnsansız Hava Araçlarının (İHA) ortak hava sahasına entegrasyonu kapsamlı bir şekilde incelenmektedir. Sistematik inceleme metodolojisi kullanılarak çalışmada yasal düzenlemeler, uçuş emniyeti ve koordinasyon ile ilgili temel zorlukları, sorunları ve olası çözümleri ortaya koymaktadır. Bulgular çok katmanlı hava sahası modelleri, dikkatli rota planlama, güvenli iletişim ağları, çatışma tespiti ve çözümü stratejileri ile yapısal olarak güçlendirilmiş düzenlemeler dahil olmak üzere çeşitli unsurların İHA entegrasyonunda kritik bir rol oynadığını göstermektedir. Ayrıca İHA'ların karmaşık hava sahalarında ve değişken koşullara uyum sağlamalarını desteklemek adına önerilen çözümleri inceleyerek Reinforcement Learning (RL) ve Human-in-the-loop Reinforcement Learning (HRL) algoritmalarının potansiyeli ortaya konmuştur. Çalışmanın sonuçları, İHA'ların hava sahasına emniyetli ve düzenli bir şekilde entegre edilmesi için araştırma projelerinin sürekli olarak yürütülmesinin, paydaş işbirliğinin ve teknoloji geliştirmelerine kararlı desteğin önemini vurgulamaktadır.

Anahtar Kelimeler: İnsansız Hava Aracı; İnsansız Hava Aracı Sistemleri Trafik Yönetimi; Otonom Araçlar; Reinforcement Learning; Sistematik İnceleme; Yapay Zeka

JEL Sınıflandırma: M10, L93, L94.

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[1] Air Traffic Controller, General Directorate Of State Airports Authority and Air Navigation Service Provider, atuncal@gmail.com

[2] Assist. Prof. Dr., İstanbul Esenyurt University, ufukerol@esenyurt.edu.tr

INTRODUCTION

The rapid evolution of Unmanned Aerial Vehicles (UAVs) has been driven by technological advancements in control, miniaturization, and computerization, resulting in the emergence of secure, lightweight, robust, and cost-efficient UAVs (Mohsan et al., 2023). This progress has led to a substantial growth in the drone industry, with UAVs finding applications in various sectors (Sharma et al., 2022). UAVs are now used for purposes such as wireless coverage, military operations, agriculture, medical services, environmental monitoring, climate research, and delivery and transportation (Adoni et al., 2023; Al-Shareeda et al., 2023). By 2035, the global market for UAVs was projected to range between $74 billion and $641 billion, driven by current applications and the potential growth of cargo and air taxi uses (Wiedemann et al., 2023).

The integration of UAVs into traditional Air Traffic Management (ATM), primarily designed for manned aircraft, poses a significant challenge (Tuncal & Uslu, 2021). This integration necessitates the development of new procedures, technologies, and regulations to ensure safe and efficient UAV operations. Moreover, the establishment of a robust framework for managing UAV traffic in lower airspace, referred to as Unmanned Traffic Management (UTM), is imperative to regulate the escalating number of UAVs effectively (Davies et al., 2021; Volkert et al., 2019).

The projected increase in delivery drones and the expected growth of the commercial small non-model UAVs worldwide have critical implications, challenges, and opportunities for both ATM and UTM. The rising use of drones and air-taxis will lead to more congested airspace, necessitating the implementation of UTM initiatives to ensure safe and efficient operations (Chin et al., 2021). Challenges related to integrating UAVs into the UTM concept within the dynamic and congested airspace alongside manned aircraft include the absence of an air navigation or air traffic control system, the risk of collisions between UAVs, the possibility of unmanaged UAVs without centralized control, and potential threats to aircraft and aviation infrastructure (Bolz & Nowacki, 2023; Rithic & Arulmozhi, 2023; Shan et al., 2023). To address these challenges, the integration of UTM with existing ATM is necessary. This integration allows for seamless coordination and communication between manned aircraft and UAVs, ensuring their safe coexistence in shared airspace (Geister & Korn, 2013; Kainrath et al., 2022; Raju et al., 2018). Integrating UTM with ATM is crucial for the safe and efficient management of both manned and unmanned aircraft in shared airspace, requiring the development of new procedures, technologies, and regulations to ensure safe and efficient UAV operations while accommodating the growing number of UAVs (Barnhart et al., 2021; Patrikar et al., 2022).

This paper aims to address a significant gap in the field of integrating UAVs into shared airspace. While existing research delves into specific aspects of this intricate challenge, a comprehensive framework that covers essential components and potential solutions is still missing. This study addresses a crucial gap by offering a systematic review of essential aspects concerning the integration of UAVs into airspace, training UAVs for dynamic environments, handling UAV emergencies and crashes, and ensuring the security of UAV communication and data transmission. By reviewing existing literature, pointing out limitations, and suggesting practical solutions, this work intends to help policymakers, researchers, and entrepreneurs navigate the complexities of UAV integration. However, the limitations of our focus, primarily on technological aspects, are acknowledged, and further exploration of the broader socio-economic and legal implications is encouraged. It is strongly believed that the transformative potential of UAVs will be unlocked and their smooth integration into our skies ensured through collaborative efforts involving various stakeholders, along with ongoing research and technological innovation.

1. METHODS AND MATERIALS

The methodology used in this study is a systematic review approach aimed at addressing the research questions related to UAV technology and its impact. This approach follows a systematic review process, which includes the formulation of research questions, the selection of appropriate databases, a clearly defined search strategy, explicit inclusion and exclusion criteria, rigorous quality assessment, and a comprehensive screening process (Ahn, & Kang, 2018; Newman, & Gough,2020). This systematic approach ensures the reliability and relevance of the literature selected for the review, facilitating a thorough examination of the challenges and solutions in UTM. Ultimately, it contributes to the safe and efficient coexistence of unmanned and manned aviation in shared airspace. The systematic review process was structured as follows.

1.1. Research Questions and Selection Criteria

To guide the literature review process, a set of research questions (Q1-Q4) was formulated, as presented in Table 1. These questions were carefully designed to investigate various aspects of UAV technology and its integration into shared airspace.

Table 1. Key Themes and Research Questions

Key Themes	Research Questions
Integration of UAVs into Airspace	How can the integration of UAVs into shared airspace be optimized?
Training UAVs for Dynamic Environments	How can UAVs be trained for safe navigation in complex environments?
Handling UAV Emergencies and Crashes	How can UAV operators and technology be better equipped to handle in-flight emergencies and crashes?
Security of UAV Communication and Data Transmission	How can UAV communication systems be optimized for maximum security and data transmission efficiency?

The selection of research questions in the study is logically based on the pivotal role they play in addressing key challenges related to UAV integration into shared airspace, focusing particularly on UTM and ATM aspects.

"Q1. How can the integration of UAVs into shared airspace be optimized?" is a fundamental question as it delves into the heart of UTM and ATM. Optimizing the integration of UAVs is crucial for ensuring the safety, efficiency, and seamless coexistence of UAVs with manned aircraft in shared airspace. It involves the development of conflict detection and resolution methods, airspace models, regulations, and communication networks, all of which are central to the effective management of air traffic in a mixed environment.

"Q2. How can UAVs be trained for safe navigation in complex environments?" is essential for the safe integration of UAVs into shared airspace. Training UAVs for complex environments involves the development of navigation and obstacle avoidance systems, which are integral to UTM and ATM. It is imperative for UAVs to adaptively respond to obstacles and changes in mission objectives to prevent accidents or incidents, ensuring the safety of both manned and unmanned aircraft.

"Q3. How can UAV operators and technology be better equipped to handle in-flight emergencies and crashes?" addresses the need for preparedness in handling emergencies, which is a vital aspect of UTM. UAV operators and technology must be well-equipped to respond to in-flight emergencies to ensure safe operations. Handling such situations plays a key role in enhancing the overall safety and risk management within shared airspace.

"Q4. How can UAV communication systems be optimized for maximum security and data transmission efficiency?" is paramount in the context of UTM and ATM. Communication systems are the backbone of air traffic management, and ensuring their security and efficiency is central to managing UAV operations in shared airspace. Optimization of communication systems contributes to data exchange, tracking, and coordination of both UAVs and manned aircraft.

In summary, these four questions have been selected for the study because they collectively address core issues related to UTM and ATM, playing a pivotal role in the integration of UAVs into shared airspace. The logical progression from optimizing integration, training UAVs, equipping operators, and optimizing communication systems ensures a comprehensive examination of the challenges and solutions in UTM, ultimately contributing to the safe and efficient coexistence of unmanned and manned aviation.

1.2. Database and Search Strategy

Database Selection: Established academic databases, including IEEE, Science Direct, EBSCO, and Web of Science, which are renowned sources for scholarly research, were systematically explored to identify relevant research.

Systematic Keyword-Based Search Method: A systematic keyword-based search approach was employed to identify pertinent publications. Specific keywords, as outlined in Table 2, were employed, focusing on UAVs. These keywords were carefully chosen to facilitate a comprehensive examination of all facets of UAV technology and its impact on shared airspace.

Table 2. Research Keywords

UAV	UAV Obstacle Avoidance
UAV Collision Avoidance	UAV Path Planning
UAV Collision Detection	UAV Regulations
UAV Communication	UAV Restrictions
UAV Conflict Detection	UAV Safety
UAV Conflict Management	UAV Security
UAV Control	UAV Navigation
UAV Data Security	UAV Technology
UAV Deployment	UAV Traffic
UAV Emergency Landing System	UAV Traffic Management
UAV Environment	UAV Trajectory
UAV Flight	UAV Trajectory Planning
UAV Incidents	Unmanned Aerial Vehicles
UAV Integration	Unmanned Traffic Management
UAV Networks	UTM

1.3. Inclusion and Exclusion Criteria

Inclusion Criteria: While formulating the inclusion criteria, our objective was to classify research papers closely relevant to UAV technology and its various dimensions. Additionally, papers that provided insightful analyses of related fields, such as autonomous systems, aviation, and communication, were considered for inclusion if they were deemed pertinent to the core study issues.

Duplicates and Quality Assessment: To ensure the quality and originality of the selected literature, a meticulous process was undertaken to identify and eliminate duplicate papers found in multiple databases. Subsequently, the selected publications underwent a rigorous assessment for both quality and significance. The final dataset was refined to exclude papers that did not conform to established scientific standards or lacked a peer-review process, thus ensuring the precision and consistency of the data gathered for this literature review.

1.4. Screening of Papers

Title Screening: In the initial phase of screening, papers were assessed based solely on their titles to determine their alignment with the predefined criteria. The primary objective of this phase was to identify papers that did not directly address the research questions.

Abstract Review: In an additional screening step, abstracts of papers for which the relevance could not be ascertained from the title alone were carefully reviewed. This step ensured that the selected papers were specifically focused on addressing the research issues.

1.5. Data Analysis

After completing the screening process, an extensive review and synthesis were conducted on the chosen papers. To offer comprehensive analyses of the research questions, it was necessary to gather and integrate data from the selected publications. The conclusions presented in this study are drawn from the literature review, which is founded upon the previously analyzed data.

2. RESULTS

Several critical aspects are covered in the findings of the systematic review. These encompass the examination of procedural and regulatory necessities for seamless UAV integration into shared airspace, with an emphasis on airspace management and compliance frameworks. Additionally, methods to train UAVs for adaptive navigation within dynamic environments are explored, along with protocols for managing emergencies and unexpected failures during UAV operations. Security measures for safeguarding UAV communication channels and data transmission against potential vulnerabilities or threats are also investigated.

2.1. Integration of UAVs into Airspace

UAVs have emerged as a transformative technology with vast potential in various industries, but their integration into shared airspace alongside manned aircraft poses complex challenges. As these autonomous systems proliferate, addressing concerns related to safety, coordination, and regulations becomes pivotal. Here are some of the key strategies and technologies that can facilitate the integration of UAVs into the airspace:

CDR methods:

An efficient and effective CDR system for UAVs can be designed using various methods proposed in the literature. One approach involves utilizing a non-rigid hierarchical discrete grid structure and coding method for spatial three-dimensional grids, which optimizes the identification ability of grid vertices, edges, and faces. This optimization results in improved conflict detection and path planning methods (Xue et al., 2023). Another method encompasses the use of a Multi-Agent Deep Deterministic Policy Gradient Algorithm (MADDPG) to train UAVs for path planning tasks under conditions of incomplete information. This approach achieves fast and accurate dynamic path planning for multiple UAVs (X. Wu et al., 2022). Furthermore, a conflict detection algorithm that considers the immediate trajectory as a straight line can be applied with nonlinear mobilities, providing acceptable performance in terms of false and missed alarms (Isufaj et al., 2022). In addition, a Multi-Agent Reinforcement Learning (MARL) approach based on graph neural networks can be used to model multi-UAV conflict resolution, allowing cooperative agents to communicate and generate resolution maneuvers (Yang et al., 2021). CDR methods are essential for solving conflicts, such as possible collisions, between UAVs of different service providers in shared airspace. State-of-the-art algorithms, such as ORCA, have been adapted for UAV operations to address practical considerations, including navigation inaccuracies, communication overhead, and flight phases (Ho et al., 2018a; 2018b).

Rule-based conflict management (RBCM):

RBCM plays a crucial role in resolving conflicts and ensuring safe UAV operations within shared airspace. This approach involves applying deconfliction methods sequentially based on predefined rules. The first stage of RBCM occurs during the generation of flight plans, where potential conflicts are identified and avoided as part of a strategic deconfliction process (Alharbi et al., 2020). The second stage, known as pre-tactical deconfliction, addresses conflicts by introducing ground delays to the UAV, effectively resolving issues (Acevedo et al., 2020). In the third stage, tactical deconfliction is employed, and UAVs temporarily hover or loiter in the last waypoint before the conflict area until the conflict time window elapses (Radanovic et al., 2019). This rule-based strategy, which differs from existing approaches, emphasizes the sequential application of deconfliction methods (Ho et al., 2018a). The design of this approach incorporates realistic airspace constraints and considers potential airspace modernization concepts (Isufaj et al., 2022).

Multilayer low-altitude airspace models:

Theoretical models of airspace, depicted as intricate multilayer networks comprising nodes and airways, offer valuable insights for grappling with the intricate challenge of UTM (Labib et al., 2019a). In the pursuit of designing a multilayer model tailored to low-altitude airspace for UAVs, the literature presents various approaches. One method entail dividing the airspace into distinct air corridors that safely circumvent buildings and obstacles. This is accomplished by mapping structures using USGS Lidar data and simulating the coordination of UAV systems as perfect fluid flow, complete with streamlines produced by solving the method known as the Laplace partial differential equation (El Asslouj et al., 2023). An alternative approach involves representing airspace as a weighted multilayer network, incorporating nodes and airways. This framework facilitates the abstract representation of UAV traffic and proves to be invaluable for conducting experimental simulations and validation (Labib et al., 2019b; Shrestha et al., 2022). Through the integration of these distinct methodologies, the development of a comprehensive multilayer low-altitude airspace model tailored to UAVs becomes feasible. Such a model holds the potential to significantly contribute to the secure and efficient administration of UAV traffic.

Path planning schemes:

Efficient pre-flight mission planning techniques and collision-avoidance algorithms are instrumental in establishing conflict-free flight paths for UAVs prior to their missions. Automating the path planning process, specifically tailored for collision avoidance, contributes significantly to ensuring both efficiency and safety in flight paths (Lamba et al., 2021). Path planning strategies for UAVs encompass a range of techniques and algorithms. One approach involves the utilization of advanced artificial intelligence techniques, notably RL, to enable UAV navigation in unstructured environments (Z. Liu et al., 2023). An alternative approach combines clothoid curves and graph theory to optimize trajectory planning for fixed-wing UAV formations in order to prevent collisions (Chronis et al., 2023). Furthermore, the application of genetic algorithms serves to compute the most efficient path distribution schemes, enhancing material distribution efficiency in critical scenarios (Blasi et al., 2023). Real-time conflict detection and intelligent resolution methods, including the multi-agent deep deterministic policy gradient algorithm, offer dynamic path planning solutions for multiple UAVs (Xue et al., 2023). Moreover, an integrated air-ground collaborative unmanned system path planning framework is a viable solution, wherein UAVs play a pivotal role in path planning for ground-based Unmanned Ground Vehicles (UGVs), particularly in search and rescue missions (Y. Sun et al., 2022).

Secure and reliable communication networks:

Establishing a secure and reliable communication network is paramount to effectively utilize hundreds or even thousands of UAVs simultaneously. Traditional satellite-based UAV communication systems exhibit limitations, including slow data transmission links, even when dealing with only a small drone fleet. Overcoming these constraints can be achieved through the strategy of local data storage on each individual drone during its mission, subsequently consolidating the collected intelligence upon its return (Bian et al., 2013). Various approaches have been proposed in the literature to design a secure and reliable communication network for UAVs. One approach center on the deployment of UAV relay networks, employing Q-learning algorithms to minimize the number of nodes and ensure communication reliability (W. Wang et al., 2023). Another approach addresses collision avoidance during UAV flight by breaking down reliable UAV services into sub-problems and leveraging interpretable artificial intelligence frameworks for transparent and trustworthy decision-making (Quan et al., 2023). Additionally, the design of secure Integrated Sensing and Communication (ISAC) systems for UAVs entails tasks such as tracking and predicting the location of legitimate users, formulating trajectory design problems, and developing efficient iterative algorithms for optimal solutions (J. Wu et al., 2023).

Regulations and guidelines:

Regulations and guidelines governing UAV operations, including flight restrictions in sensitive areas and safety requirements, should be seamlessly integrated into existing aviation regulations. This integration is crucial to ensure uniformity and safety within shared airspace (Çınar&Tuncal, 2023; Ho, 2018a; 2018b). Designing UAV regulations and guidelines necessitates a tailored approach, accounting for specific applications, measurement objectives, and an assessment of measurement uncertainty (Balestrieri et al., 2021). It is imperative to confront critical challenges, including privacy, safety, security, public inconvenience, and trespassing. Comparing these regulations against predefined criteria is essential to identify any potential shortcomings (McTegg et al., 2022). Additionally, the formulation of guidance laws, based on robust feedback linearization principles, can ensure the autonomous navigation of UAVs towards predetermined waypoints, even in the presence of external disturbances like wind gusts (Y.Y. Chen et al., 2014). The development of comprehensive national legislation becomes paramount, particularly in distinguishing between the recreational and commercial utilization of UAVs and attributing responsibility to the pilot for any accidents or incidents (Cracknell, 2017). Aligning UAV regulations with a country's specific needs and applications is fundamental in facilitating the effective use of UAVs and promoting overall progress (Shrestha et al., 2019).

Trajectory coordination:

Equipping UAVs with decision capabilities to update their trajectories (4D contracts) when facing unpredictable events or when priority trajectories are added to the airspace can help improve coordination and deconfliction into shared airspace (Picard, 2022). Trajectory coordination for UAVs can be designed by employing multiple UAVs coordinated by a base station to help ground users offload their sensing data (Gong et al.,2023). The trajectory planning aims to collect all ground users' data, while the network formation optimizes the multi-hop UAV network topology to minimize energy consumption and transmission delay (J. Xu et al., 2022; Shi et al., 2022).

In conclusion, the successful integration of UAVs into shared airspace requires a multifaceted approach that encompasses conflict detection and resolution methods, rule-based conflict management, the development of multilayer low-altitude airspace models, advanced path planning schemes, secure communication networks, and robust regulations and guidelines. Furthermore, trajectory coordination mechanisms are crucial in enhancing coordination and deconfliction among UAVs. By leveraging these strategies and technologies, we can ensure that UAV operations not only coexist safely with manned aircraft but also contribute to the growth of industries and applications that benefit from the use of UAVs. As the UAV market continues to evolve, these integrated approaches are essential for optimizing their integration into shared airspace.

2.2. Training UAVs for Dynamic Environments

Training UAVs to navigate complex, dynamic environments and dynamically adjust their flight trajectories when confronted with unforeseen obstacles or alterations in mission objectives can be accomplished through a range of methodologies. These strategies empower UAVs to effectively respond to unexpected challenges or shifts in their mission goals, thereby enhancing their overall performance and safety within intricate and ever-changing environments. Here are some of the approaches that have been explored:

RL algorithms:

RL algorithms, including Deep Q Learning, Actor-Critic (AC), and Advantaged Actor-Critic (A2C), have found applications in training UAVs for automatic obstacle avoidance and the optimization of avoidance decision-making models in complex scenarios (Han et al., 2019; Zhang et al., 2023b). These RL algorithms employ modular learning, where intricate tasks are decomposed into simpler components, allowing individual learning before interconnecting them and safe navigation and avoidance of dynamic obstacles (Z. Xu et al., 2022). UAVs can be trained using Deep Reinforcement Learning (DRL) algorithms to autonomously adapt their flight trajectories in complex environments and in response to changes in mission objectives (Ye et al., 2023). This approach accelerates learning and facilitates the transfer of information between modules (Choi et al., 2023).

Combining RL with Multi-Objective Evolutionary Algorithms (MOEAs):

The RL and MOEAs has emerged as a promising strategy for enhancing autonomous UAV navigation in large-scale complex environments (An et al., 2023). This integration seeks to generate a diverse set of non-dominating parameters for the reward function, ultimately leading to versatile decision-making preferences, improved convergence, and enhanced performance. RL algorithms have been tailored to combine with multi-objective evolutionary algorithms for UAV applications. One approach involves the utilization of a decentralized partially observable Markov decision process (Dec-POMDP) model and multi-agent RL, specifically employing a parametrized deep Q-network (P-DQN) for the action space. The QMIX framework aggregates local critics of each UAV, contributing to an effective combination (Yin, & Yu, 2021). Another avenue of exploration is the amalgamation of evolutionary strategies with the off-policy DRL algorithm TD3. This innovative approach incorporates a multi-buffer system to enable unhindered exploration in the policy search space, contributing to the effective convergence of algorithms (Altin, 2020; Callaghan, 2023). Furthermore, a genetic algorithm-based K-means (GAK-means) algorithm is proposed for cell partitioning, complemented by Q-learning-based deployment and movement algorithms to facilitate 3-D positioning and dynamic movement of UAVs (X. Liu et al., 2019). These approaches represent a concerted effort to harness the synergies between RL and evolutionary algorithms for UAV applications, paving the way for improved performance and navigation in complex environments.

HRL algorithms:

HRL offers a dynamic approach to adapting UAV reward functions for obstacle avoidance, reducing training convergence time, and enhancing efficiency and precision in large-scale 3D complex environments (G. Li et al., 2023). To implement HRL for UAVs, DRL techniques are combined with human expertise. In HRL, humans play a pivotal role in defining reward functions and decision-making related to problem-solving and deploying learned solutions (Taylor, 2023). In tasks involving continuous action spaces, a Q value-dependent policy (QDP)-based HRL algorithm can be utilized. Here, human experts selectively provide guidance to the agent during the early stages of learning, significantly improving learning speed and performance in continuous action space tasks (B. Luo et al., 2023). Furthermore, trajectory design mechanisms are employed to optimize the energy efficiency of UAV- aerial base stations in 3D space, where RL algorithms like multi-armed bandit with upper confidence bound contribute to this optimization (Arani et al., 2021).

Heuristic dynamic reward functions:

Designing heuristic dynamic reward functions is instrumental in guiding UAV navigation and enhancing obstacle avoidance capabilities, particularly in scenarios like ultra-low altitude flight in complex environments for missions (Zhang et al., 2023a; 2023b). The design of heuristic dynamic reward functions for UAVs can encompass various approaches. For instance, incorporating situational information such as angle and speed can address the challenge of sparse rewards, thereby aiding convergence (Xie et al., 2022). Another strategy involves constructing and estimating simplified trajectories to the target using third-order Bezier curves, applicable in both two-dimensional and three-dimensional virtual environments (Tovarnov & Bykov, 2022). Furthermore, the redesign of reward functions based on the state space and the acquisition of status information through vehicle cameras can enhance agent learning efficiency and convergence in image-based end-to-end vehicle following methods (Xiao et al., 2022). The concept of heuristic reward function design involves providing additional rewards beyond those supplied by the underlying Markov Decision Process, expediting the learning system's progress (Wei et al., 2004).

Combining neural networks with Interfered Fluid Dynamical System (IFDS):

The integration of neural networks and IFDS has been proposed for real-time obstacle avoidance within three-dimensional dynamic complex environments, wherein the neural network is utilized to adapt the coefficients of the IFDS in response to the environmental conditions (Y. Wang et al., 2020). To enhance UAV performance, neural networks can be combined with IFDS. One approach involves the utilization of neural networks to dynamically modify the IFDS coefficients based on the surrounding environment (Celestini et al., 2022). This enables UAVs to flexibly adjust their flight trajectories to circumvent obstacles in intricate three-dimensional settings (Y. Wang et al., 2020). Another approach entails the use of neural networks to mitigate inversion errors in the control system arising from uncertainties in UAV and actuator dynamics (Wijnker et al., 2019). By employing neural networks to compensate for parameter uncertainties and disturbances, this approach enhances the robustness and accuracy of attitude and trajectory control (Xiang et al., 2016). These amalgamations of neural networks and IFDS hold promise for optimizing UAV trajectories and ensuring safety in dynamic environments (J. Sun et al., 2021).

In conclusion, the training of UAVs for safe navigation in complex environments is achievable through a spectrum of strategies, including RL algorithms, the integration of RL with MOEAs, HRL, heuristic dynamic reward functions, and the combination of neural networks with IFDS. These methodologies empower UAVs to dynamically adapt their flight trajectories in response to evolving scenarios, ensuring their ability to navigate safely in the presence of unforeseen obstacles. By harnessing the power of these training approaches, UAVs are better equipped to excel in intricate, ever-changing environments, enhancing their performance and safety in diverse applications.

2.3. Handling UAV Emergencies and Crashes

In the ever-evolving realm of UAV technology, the imperative of ensuring safety and efficiency has gained paramount importance. This section casts a spotlight on a spectrum of pivotal elements within UAV systems, spanning from crafting emergency landing procedures and real-time monitoring and communication solutions to the development of collision avoidance systems and robust mechanisms for investigation and reporting. Each of these facets addresses distinct challenges and advances, collectively contributing to the enhancement of safety and performance in the realm of UAVs.

Emergency landing procedures:

In terms of flight safety, the landing is the most important aspect of a routine flight (Saraçyakupoğlu et al., 2020). UAVs should be equipped with robust emergency landing procedures to ensure their safe descent in the event of system failures or other emergencies. Various approaches can be employed to design these emergency landing procedures, each catering to specific challenges and safety considerations. One approach involves leveraging depth maps obtained from RGB-d cameras to identify suitable landing platforms, particularly in intricate ground environments (Bu et al., 2022). Another innovative method utilizes real-time semantic segmentation networks to classify terrain and determine optimal landing spots based on safety evaluations (T. Wang et al., 2023). DRL is another promising avenue to detect secure landing sites and autonomously guide UAVs to a safe landing, while considering various safety constraints (Bartolomei et al., 2022). Additionally, a waypoint path planning method based on terminal velocity prediction can be employed to chart a secure landing path for UAVs during emergencies (Kim et al., 2020). Furthermore, an offline semi-automated approach may be adopted to identify suitable emergency landing sites along UAV flight paths, with considerations for factors such as surface type and prevailing wind conditions (Ayhan et al., 2018).

Real-time monitoring and communication:

UAV operators must be equipped with real-time monitoring and communication capabilities to effectively respond to emergency situations. Designing real-time monitoring and communication solutions for UAVs involves the integration of various technologies, each contributing to improved situational awareness and decision-making. One innovative approach is optimizing UAV trajectory design to serve as both downlink transmitters and radar receivers. This allows for real-time tracking and predictive location assessment based on delay measurements extracted from sensing echoes (J. Wu et al., 2023). Another avenue leverages the fusion of UAV technology with modern 4G/5G communication networks. Key technologies such as multi-base station relay, antenna optimization, and PTZ measurement and control are harnessed to meet real-time and remote interaction requirements effectively (Q. Li et al., 2022). Furthermore, the integration of Software-Defined Networks (SDN) with Digital Twin (DT) technology offers capabilities for real-time monitoring, network performance analysis, and virtualization. This revolutionary combination transforms the design, implementation, and maintenance of software-defined UAV networks, enhancing their agility and adaptability (Abir & Chowdhury, 2023).

Collision avoidance systems:

UAVs are required to be equipped with collision avoidance systems that enable them to detect and evade other aircraft or obstacles, especially when faced with potential collision scenarios (Lamba et al., 2021). Developing collision avoidance systems for UAVs involves diverse methodologies and technologies to enhance their safety measures. One such approach involves the use of Computational Fluid Dynamics (CFD) simulation software to analyze the impact of integrating anti-collision devices on UAVs. This analysis delves into their hovering capabilities, flow field characteristics, and aerodynamic configurations (X. Li et al., 2023). An alternative methodology is the combination of DRL with global planning to establish a hybrid collision-avoidance mechanism. This hybrid system is geared towards real-time navigation in intricate environments, ensuring efficient obstacle avoidance (C. Zhang et al., 2023). Furthermore, an intelligent game theory-based collision avoidance method is employed, characterized by the design of a suitable controller through a pay-off function. The purpose is to achieve a stable positioning of UAVs without collision incidents (Maurya et al., 2022). In addition to these approaches, the Force Field Protocol (FFP) is introduced, incorporating artificial potential fields and wireless communication. FFP serves to autonomously detect and maintain a safe separation distance between UAVs, enhancing collision avoidance (Wubben et al., 2023). Lastly, genetic algorithms play a vital role in the autonomous collision avoidance process. These algorithms are instrumental in optimizing collision avoidance paths, thus ensuring the safety of UAV flights (Y. Sun & Dang, 2022).

Investigation and reporting:

UAV operators should be required to investigate and report any emergencies or crashes to the appropriate authorities for further analysis and improvement of safety measures. Procedures and mechanisms that can enhance the investigation and reporting of UAV emergencies or crashes by operators include the use of data field analysis and natural language processing algorithms to automate the analysis of reported issues and extract keywords from reports (Khan et al., 2022). The Human Factors Analysis and Classification System (HFACS) can be combined with an Analytical Hierarchical Process (AHP) decision-making model to assess the risk of accidents and identify causes. Clear regulations and procedures for reporting and analyzing UAV incidents are necessary to improve the safe integration of unmanned and manned aviation (Alharasees et al., 2022). Additionally, raising awareness among UAV users about the need to report incidents and involving them in the investigative process can contribute to the assessment and development of strategies for integrating manned and unmanned aviation (Konert & Kasprzyk, 2021).

In conclusion, the safe integration of UAVs into shared airspace demands a holistic approach that encompasses various critical elements. Robust emergency landing procedures, real-time monitoring and communication solutions, advanced collision avoidance systems, and effective mechanisms for investigation and reporting are vital components of this approach. By combining these strategies, UAV operators and technology can better prepare for and respond to in-flight emergencies and crashes, thereby contributing to the overall safety and efficiency of UAV operations within shared airspace. As the UAV industry continues to evolve, the continued development and implementation of these measures are essential for the seamless coexistence of unmanned and manned aviation.

2.4. Security of UAV Communication and Data Transmission

In an era marked by the increasing demand for secure and efficient communication within UAV networks, a multitude of challenges and innovative solutions have come to the forefront. This section delves into several critical aspects of UAV communication systems, addressing issues such as limited bandwidth, Line-of-Sight (LoS) vulnerabilities, covert communication, quantum security, and resilience to attacks. These challenges have prompted the development of diverse strategies and technologies aimed at enhancing the security and effectiveness of UAV communications.

Limited bandwidth:

Traditional satellite-based UAV communication systems have notable limitations, including slow data transmission links, even in scenarios involving a limited number of drones (Bian et al., 2013). This restricted bandwidth poses challenges for the real-time transmission of collected information, necessitating alternative strategies. One approach involves storing data locally on each drone during its mission and consolidating this information upon the UAVs' return. The limited bandwidth available for UAVs can be addressed through the utilization of various techniques aimed at enhancing communication security and data transmission. Techniques such as wireless power transfer, physical layer security, and trajectory optimization play a crucial role in maximizing system utility, improving secrecy rates, and minimizing information eavesdropping. Moreover, deploying multiple UAVs can optimize coverage and offloading, considering various user tasks and preferences related to residual energy and processing delay (Lu et al., 2022). For further enhancement, a joint optimization approach can be applied, considering wireless charging duration, trajectory, and transmit power. This optimization accounts for factors such as limited battery capacity, maximum flying speed, and energy-harvesting causal constraints (Tang et al., 2021). Furthermore, the optimization of trajectory, flight duration, and user scheduling can significantly improve energy efficiency while considering constraints related to eavesdropping rate and outage probability for secure data transmission (X. Chen et al., 2023).

LoS vulnerabilities:

UAV-assisted communication frequently relies on LoS air-ground channels, which are susceptible to attacks by malicious users (Jiang et al., 2021). This heightened vulnerability of LoS channels necessitates the development of techniques to ensure secure communication in such scenarios. To address LoS vulnerabilities for UAVs and enhance secure communication and data transmissions, various approaches have been proposed in the literature. One strategy involves optimizing the UAV's trajectory and flight duration to maximize energy efficiency and ensure the freshness and security of transmissions (X. Chen et al., 2023). Another method focuses on robust trajectory planning, considering the presence of multiple jammers and imperfect power and location information. The objective here is to maximize the worst-case Signal-to-Interference-plus-Noise Ratio (SINR) (Lingyun et al., 2022). Moreover, telemetry performance between UAVs and ground control stations can be analyzed to assess Received Signal Strength Indicator (RSSI) values and identify factors that may lead to degraded performance, such as voltage drops and interference from cellular base stations (Chasanah et al., 2022). Furthermore, a dual-UAV aided secure dynamic ground-to-UAV communication system can be designed. This approach involves optimizing UAV trajectories and ground devices transmit power to maximize the sum secrecy rate (Kang et al., 2022).

Covert communication:

Covert communication, which aims to conceal the existence of transmissions, is a critical requirement for enhancing security (Jiang et al., 2021). In UAV-assisted networks, achieving covert communication is particularly challenging due to the open and broadcasting nature of wireless channels. The development of effective techniques for covert communication in UAV networks is an active area of research. One approach to achieving covert communication in UAV networks leverages the high flexibility of UAVs for long-distance covert transmission. This is accomplished by dividing the transmission into two phases and optimizing transmit power and block length to meet the covertness requirement. Furthermore, the UAV's location can be optimized to maximize effective throughput while considering constraints related to transmit power and block length. Simulation results have demonstrated the effectiveness of this UAV relaying scheme in ensuring covert transmission (H. Luo et al., 2023). Another method involves the use of blockchain and digital twin technology to enhance the security of UAV networks. By mapping physical UAVs into Cyberspace, a virtual UAV network known as CyberUAV is created. In CyberUAV, a blockchain consensus mechanism called Proof of Network Coding (PoNC) is employed to ensure security. Analysis and simulations have illustrated the advantages of this approach in terms of both efficiency and security for UAV networks (Lu et al., 2022).

Quantum security:

As the demand for instantaneous and enhanced security continues to grow, researchers have been delving into the potential of quantum cryptography to secure UAV communications (Ralegankar et al., 2021). Implementing quantum security in practical UAV communication systems, however, comes with significant challenges, primarily the need for robust and efficient transmission protocols. Quantum security harnesses the principles of quantum communication and cryptography to ensure the security of communication and data transmissions for UAVs. Quantum communication, specifically Quantum Key Distribution (QKD), provides an exceptionally secure method for transmitting cryptographic keys. This approach safeguards the keys used for encrypting and decrypting UAV communications from eavesdropping or interception. Notably, quantum cryptography can offer unconditional security, protecting data and communications from potential threats posed by quantum computers (Kumar et al., 2023). In addition to this, quantum technologies can be applied to authenticate the identities of entities involved in UAV communication and establish secure communication channels (Conrad et al., 2023). Furthermore, quantum secure communication protocols, such as Quantum Secret Sharing (QSS), can be utilized to store highly sensitive and confidential information (Abulkasim et al., 2022). By integrating these quantum security measures, UAVs can attain robust protection for their communication and data transmissions.

Resilience to attacks:

UAV communication systems must exhibit resilience to a range of potential attacks, including jamming, eavesdropping, and data manipulation. One notable approach to bolstering this resilience is the development of a Resilience Oriented Security Inspection System (ROSIS), which is designed to enhance the security of data access and sharing among Urban Air Mobility (UAM) systems, including aircraft and Air Traffic Service Providers (ANSPs) (Wei et al., 2023). Another method involves the application of RL algorithms to optimize the secure offloading of tasks to UAVs within multi-UAV-assisted mobile edge computing systems. This optimization process considers factors like user task preferences related to residual energy and processing delays (Lu et al., 2022; Wei et al., 2023). Furthermore, defensive strategies can be employed to counteract jamming attacks and ensure secure data collection in Internet-of-Things (IoT) networks. These strategies may include the adoption of higher SINR thresholds and the utilization of intelligent UAV jammers (Lu et al., 2022).

In summary, the multifaceted landscape of UAV communication systems presents various challenges, from limited bandwidth and LoS vulnerabilities to covert communication, quantum security, and resilience to attacks. Researchers and innovators continue to explore cutting-edge solutions to address these challenges and fortify the security and efficiency of UAV communications, paving the way for the continued integration of UAVs into our evolving technological landscape.

3. CONCLUSION AND DISCUSSION

The integration of UAVs into shared airspace is a multifaceted challenge, characterized by complexities related to safety, coordination, and regulatory frameworks. A comprehensive framework, as discussed earlier, encompasses various strategies, such as CDR methods, RBCM, multilayer airspace models, path planning, secure communication networks, and regulations. These elements, coupled with trajectory coordination, collectively enhance the safe integration of UAVs into shared airspace, enabling them to harmoniously coexist with manned aircraft across diverse industries. This integrated approach is pivotal for harnessing the transformative potential of UAV technology.

The training of UAVs to navigate complex environments safely and adaptively respond to unforeseen obstacles or mission alterations relies on a diverse array of methodologies. Notably, the application of RL algorithms, both independently and in conjunction with MOEAs, has exhibited promise in elevating UAV navigation capabilities. Furthermore, the concept of HRL, which involves the integration of human expertise and guidance into the learning process, offers dynamic adaptability for UAV reward functions and obstacle avoidance. These methodologies collectively contribute to the enhancement of UAV performance and safety within intricate and dynamic environments, empowering UAVs to effectively address unexpected challenges and contribute to the field of autonomous UAV navigation.

Ensuring the safe integration of UAVs into shared airspace demands a holistic strategy that encompasses several critical elements. Robust emergency landing procedures, real-time monitoring, communication solutions, advanced collision avoidance systems, and effective mechanisms for investigation and reporting are pivotal components of this approach. By amalgamating these strategies, UAV operators and technology can better prepare for and respond to in-flight emergencies and crashes, ultimately contributing to the overall safety and efficiency of UAV operations within shared airspace. As the UAV industry continually evolves, the ongoing development and implementation of these measures remain indispensable for the seamless coexistence of unmanned and manned aviation.

The evolving landscape of UAV communication systems introduces a diverse array of challenges, including issues related to limited bandwidth, LoS vulnerabilities, covert communication, quantum security, and resilience to attacks. In response to these challenges, researchers and innovators are actively exploring cutting-edge solutions to bolster the security and efficiency of UAV communications. These advancements play a pivotal role in facilitating the seamless integration of UAVs into our ever-evolving technological environment. As the demand for secure and efficient communication within UAV networks continues to grow, these pioneering efforts are instrumental in shaping the future of UAV technology and its multifaceted applications.

In conclusion, this paper explores the complexities of incorporating UAVs into shared airspace and reveals how complex this process is. The results are well-received by scholars, policymakers, and business professionals, opening the door to important developments.

Firstly, our research emphasizes how crucial it is to have a thorough framework with coordination and safety as its cornerstones. A variety of methods, such as risk-based collision management, layered airspace models, and cooperative decision-making techniques, should serve as the cornerstone upon which this framework is constructed. Robust regulations and secure communication networks also need to be deeply embedded in this framework.

Secondly, the research highlights the exciting possibilities for UAV training that come with human-in-the-loop and reinforcement learning techniques. These advanced techniques enable UAVs to operate in shared airspace more safely and effectively by enabling them to maneuver through challenging environments with resilience and agility.

Thirdly, to ensure the safety of UAV operations, the research highlights the critical importance of strong protocols, real-time monitoring, sophisticated collision avoidance systems, and exhaustive investigative mechanisms. Depending on the environment can be created and the smooth integration of UAVs into our skies can be aided by putting these precautions into place.

Fourthly, the results show how UAV communication presents an intricate balance between opportunities and challenges. Researchers are working hard to improve security and efficiency because they know how important they are to the smooth coexistence of manned aircraft and UAVs.

The study defines a useful framework for additional research in the field of UAV integration. Future research efforts are directed by its insights toward the creation of resilient traffic management systems, sophisticated AI-powered operations, and cutting-edge communication technologies targeted to the particular requirements of UAV applications. We hope that this work will act as a catalyst for the advancement of UAV integration into a future marked by efficiency, safety, and harmony for researchers, policymakers, and industry professionals.

Nomenclature

A2C: Advantaged Actor-Critic
AC: Actor-Critic
AHP: Analytical Hierarchical Process
ANSP: Air Navigation Service Provider
ATM: Air Traffic Management
CDR: Conflict Detection and Resolution
CFD: Computational Fluid Dynamics
DRL: Deep Reinforcement Learning
DT: Digital Twin
FFP: Force Field Protocol
HFCAS: Human Factors Analysis and Classification System
HRL: Human-in-the-loop Reinforcement Learning
IFDS: Interfered Fluid Dynamical System
IoT: Internet-of-Things
ISAC: Integrated Sensing and Communication
LoS: Line-of-Sight
MADDPG: Multi-agent Deep Deterministic Policy Gradient Algorithm
MARL: Multi-Agent Reinforcement Learning
MOEA: Multi-Objective Evolutionary Algorithm
PoNC: Proof of Network Coding
QDP: Q Value-Dependent Policy
QKD: Quantum Key Distribution
QSS: Quantum Secret Sharing
RBCM: Rule-Based Conflict Management
RL: Reinforcement Learning
ROSIS: Resilience Oriented Security Inspection System
RSSI: Received Signal Strength Indicator
SDN: Software-Defined Networks
SINR: Signal-to-Interference-plus-Noise Ratio
UAM: Urban Air Mobility
UAV: Unmanned Aerial Vehicle
UGV: Unmanned Ground Vehicle
UTM: Unmanned Traffic Management

Author Contributions

Arif TUNCAL: Literature review, Methodology, Data curation, Formal analysis, Editing, Writing, Validation

Ufuk EROL: Supervision, Editing, Critical review, Validation, Finalization.

Conflict of Interest

The authors declare no conflict of interest.

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