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A review of global and regional frameworks for the integration of an unmanned aircraft system in air traffic management

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A B S T R A C T

Unmanned aircraft system (UAS) applications have increased exponentially in recent years owing to their low cost, improved performance, and the use of advanced technology in this relatively new and rapidly evolving industry. Despite the advanced technologies used in UASs, the integration of UASs into the air traffic management regulatory framework is lacking, which affects air transport. International and regional air transport regulators, having identified the major technological challenges, are gradually developing fundamental principles for the consolidation of manned and unmanned air traffic. In this review, the development of a common framework and fundamental principles set by major international regulatory authorities (International Civil Aviation Organization and Joint Authorities for Rulemaking on Unmanned Systems) were examined. The related initiatives of major Eastern countries (Russia, China, and Japan) in comparison with Western states (European Union (EU), United States, and United Kingdom) were comprehensively reviewed, focusing on EU activities and projects related to the concepts of operations. Indicative research activities on technology challenges (detect and avoid; command, control, and communication; and artificial intelligence-based unmanned aerial vehicle navigation), jointly identified by all international and national regulatory authorities, were also examined and presented. A comparative analysis of the fundamental principles of the frameworks revealed the similarities and differences between the approaches to the concept and its implementation. In terms of differences, the novel findings and contributions of this review are the different approaches regarding the roles and responsibilities of state authorities in unmanned aircraft traffic management (UTM) as well as approaches for UTM integration into the existing air traffic management systems. Based on this research, scientific groups of regulatory authorities could consider comparing the concepts and frameworks detailed in this review to address the differences and develop a harmonized global UTM framework.

Introduction

In recent years, the technological development of unmanned aircraft has had a significant impact on civil aviation, particularly air transport, owing to the advancement of functions and capabilities at an increasing rate. This has created a plethora of requests from government agencies

Abbreviations: A3C, asynchronous advantage actor–critic; ACO, ant colony optimization; AGL, above the ground level; AI, artificial intelligence; ANSP, air navigation service provider; API, application programming interface; ASSURED UAM, Acceptance, Safety, and Sustainability Recommendations for Efficient Deployment of Urban Air Mobility; ATM, air traffic management; BVLOS, beyond the visual line of sight; C2, command and control; CAA, civil aviation authority; CAAC, Civil Aviation Administration of China; CIS, communication and information system; CNN, convolutional neural network; CONOPS, concepts of operations; CORUS, Concept of Operation for EuRopean UTM Systems; DAA, detect and avoid; DL, deep learning; DNN, deep neural network; DRL, deep reinforcement learning; EASA, European Aviation Safety Agency; EU, European Union; eVTOL, electric vertical take-off and landing; 5G, fifth generation; FAA, Federal Aviation Administration; GA, genetic algorithm; ICAO, International Civil Aviation Organization; ICT, information and communication technology; IoT, Internet of Things; JARUS, Joint Authorities for Rulemaking on Unmanned Systems; JUTM, Japan Unmanned System Traffic and Radio Management Consortium; LOS, line of sight; M2M, machine-to-machine; MDP, Markov decision process; MPSO, modified PSO; NASA, National Aeronautics and Space Administration; ODD, operational design domain; PSO, particle swarm optimization; RL, reinforcement learning; SDSP, supplementary data service provider; S&A, sense and avoid; SESAR, Single European Sky ATM Research; SESAR JU, Single European Sky ATM Research Joint Undertaking; TCL, technical capability level; UAS, unmanned aircraft system; UOMS, UAS operation management system; USP, unmanned aircraft service providers; UAM, urban air mobility; UAV, unmanned aerial vehicle; UTM, unmanned aircraft traffic management; VLL, very low-level; VLOS, visual line of sight; X-TEAM D2D, eXTEnded AtM for Door2Door travel.

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and regulators to allow drone flights in low-altitude airspaces, where drone operations are generally limited in number and range. At the current rate, unmanned aircraft system (UAS) flights are expected to outnumber manned aircraft flights, which has forced all international civil aviation regulators to address the issue of integrating unmanned aircraft into the air traffic management (ATM) system. International, regional, and national regulatory authorities have begun to develop frameworks and concepts of operations to safely and securely integrate UASs into ATM systems, while also funding scientific research to address relevant technological challenges. The above initiatives use slightly different approaches to implement this concept and address technological challenges, and are at different stages of maturity. The aim of this paper is to review the main frameworks and concepts used in this context, compare the key ideas and implementation approaches, and discuss the remaining technological challenges. A clear understanding of the differences between these approaches is necessary for creating a harmonized global unmanned aircraft traffic management (UTM) framework.

From an international perspective, the common framework developed by the International Civil Aviation Organization (ICAO), as well as the similar works of the Joint Authorities for Rulemaking on Unmanned Systems (JARUS), have been considered to support the organization, coordination, and management of unmanned aircraft operations in real or near real time, to harmonize the standards and provide guidance material to support the creation of national UAS regulations. In this review, the initiatives of the Russian Federation, China, and Japan related to the development of a regulatory framework and concept of operations (CONOPS) were examined. The United Kingdom (UK) open-access UTM framework, the United States (US) UTM Technical Capability Levels, and the European Union (EU) U-space CONOPS were reviewed and compared, focusing on the research activities and major projects (Concept of Operation for EuRopean UTM Systems [CORUS]; CORUS-XUAM; eXTEnded AtM for Door2Door travel [X-TEAM D2D]; Acceptance, Safety, and Sustainability Recommendations for Efficient Deployment of Urban Air Mobility [ASSURED UAM]; and PJ34 AURA) of the EU, for the development of the concepts of operations. Almost all international and national regulatory authorities have defined several common challenges faced in the current technology, such as detect and avoid (DAA), artificial intelligence (AI)-based unmanned aerial vehicle (UAV) navigation, Internet of Things (IoT), and geo-awareness/geofencing, which are discussed in detail in this review, with a special emphasis on EU research activities. Furthermore, a comparative analysis between the EU and US fundamental principles of the frameworks was performed, which revealed similarities and differences in approaches to the concept and its implementation.

ICAO — common framework

The concept of a UTM system was proposed in 2016 by the members of government research agencies and industry to support the organization, coordination, and management of unmanned aircraft operations in real or near real time, including the ability to control multiple operations beyond the visual line of sight (BVLOS). It is anticipated that civil aviation authorities (CAAs) and air navigation service providers (ANSPs) will provide real-time information on airspace restrictions and the intentions of other aircraft to UAS controllers and their remote pilots in the framework of the UTM, either directly or through unmanned aircraft service providers (USPs) (International Civil Aviation Organization, 2021). The UAS operator is responsible for safely managing the flight and operations of the UAS within these constraints, without receiving positive air traffic control services from ANSPs. The primary means of communication and coordination among ANSPs, USPs, supplementary data service providers (SDSPs), UAS operators, remote UAS pilots, and other stakeholders are distributed networks of highly automated systems via preprocessing interfaces.

The common framework with core principles for global harmonization is intended to provide a framework and basic capabilities of a "standard" UTM system to states considering the implementation of a UTM system (International Civil Aviation Organization, 2021). The objective of the UTM is the safe, cost-effective, and efficient management of unmanned aircraft operations through the provision of systems and operations as well as a seamless set of services in cooperation with all parties while involving both airborne and ground-based operations. Similar to the ATM system used for manned aviation, the UTM should provide an integrated ecosystem of people, information, technology, facilities, and services supported by air, ground, and/or space communications, navigation, and surveillance (International Civil Aviation Organization, 2017). According to the ICAO common framework, any UTM system should be able to interact with the existing ATM system in the short term and fully integrate with the ATM system in the long term. The introduction and traffic management of drones and the development of the relevant UTM infrastructure should not adversely affect the safety or efficiency of the existing ATM systems.

The existing ATM systems are well-understood systems that have been used for many years for safe and efficient airspace management and aircraft operations based on airspace planning principles and cooperative systems between pilots and air traffic controllers with clear roles and responsibilities (International Civil Aviation Organization, 2021). UTM systems should be developed in conjunction with the existing ATM systems to support safe and efficient operation. Among other characteristics, the UTM system can be considered a collection of services intended to ensure the safe and efficient operation of unmanned aircraft within the UTM-approved volume of airspace (International Civil Aviation Organization, 2017). The common framework of the ICAO does not identify the technologies associated with these services but provides suggested types of services. These services are based on what is required in a given geographic volume of airspace as well as the risk of operations and the level of resilience required (International Civil Aviation Organization, 2021). Based on the operational plans that have been developed, it is evident that these services may be provided by third-party UAS traffic management service providers, ANSPs, or even government agencies and may include activity reporting, aeronautical information, airspace clearance, tracking, registration, restriction management, and tracking and positioning services. Of particular importance are collision management and avoidance services (International Civil Aviation Organization, 2005), which include strategic collision avoidance, tactical separation with manned aircraft, collision advisory and warning, compliance monitoring, and dynamic rerouting.

JARUS

JARUS has 66 member organizations and 64 countries, along with the European Aviation Safety Agency (EASA) and EUROCONTROL (as of July 2023). JARUS was established in 2012, and its primary objectives are to harmonize the standards and provide guidance to support the creation of national UAS regulations. Specifically, they proposed operational, safety, and technical regulations that primarily focus on UAVs weighing less than 150 kg. Some of the most recent publications of JARUS include the Methodology for Evaluation of Automation on UAS Operations (Joint Authorities for Rulemaking of Unmanned Systems, 2023), JARUS recommendations for UAS RPC CAT A and CAT B (Joint Authorities for Rulemaking of Unmanned Systems, 2019), the required command and control (C2) performance concept (Joint Authorities for Rulemaking of Unmanned Systems, 2016), and recommendations for personnel licensing (Joint Authorities for Rulemaking of Unmanned Systems, 2015). Management of multiple simultaneous UA flight operations (MSO) containing a set of recommendations is currently under external consultation. MSO requires a high level of automation because it is not possible for humans to have sufficient management of each unmanned aircraft participating in this operation and to ensure safe operation for all participants in the operational environment without the support of systems performing automated and/or autonomous functions.

The JARUS Methodology for Evaluation of Autonomy for UAS Operations (Joint Authorities for Rulemaking of Unmanned Systems, 2023), issued by the JARUS Automation WG, supports the classification and evaluation of the dependencies of automated/autonomous functions. The methodology indicates that the integration of UAS into airspace presents complex challenges owing to the wide variety of systems and their capabilities. Providing a single classification scheme for automation levels is difficult in this complex and varied environment; however, if a common understanding of UAS capabilities and limitations is developed, we can work towards safe and efficient integration of UAS into the airspace.

According to the JARUS Methodology, the solution to this problem is the operational design domain (ODD). The OOD supports the operational boundary definition within which a particular system or function is described to operate. Using the ODD, designers, operators, and regulators can assess the capabilities of an ATM system, a particular UAS operation, a specific UAS, or a subsystem or function within a UAS. Nevertheless, it is worth mentioning that contemporary aircraft are highly integrated platforms with several different modes of operation and capabilities depending on the onboard IT systems, resulting in different levels of automation used for the same task in different contexts. The ODD could be used for simplifying complicated functional relationships, such as describing the level of automation in the "follow-me-mode," which is challenging because it involves multiple functions at different levels. Every component of the ODD operation, such as controlling flight dynamics and sensing humans, can be mapped to a distinct level of automation.

EU — U-space

Based on the so-called "Warsaw Declaration" (European Commissioner et al., 2016), which urges further development of the potential of drone services to support EU competitiveness and global leadership, the EU has tasked Single European Sky ATM Research Joint Undertaking (SESAR JU) to develop the general concept of "U-space." The U-space was presented in the "European Drones Outlook Study: unlocking the value for Europe" (Single European Sky ATM Research Joint Undertaking, 2017), with a primary objective of ensuring the safe integration of UASs in airspace while maintaining the same level of flight safety. In its final deployment, the U-space allows complex UAS operations to be performed with a high degree of automation in all types of operational environments, including urban areas (SESAR Joint Undertaking, 2017). With this initiative, the EU launched a series of activities across Europe to develop appropriate rules and regulations and identify technical and operational requirements to support future autonomous operations.

The purpose of integrating drones (civil and military) into European airspace is the seamless conduct of air operations in all classes of airspace together with manned aircraft, in accordance with the provisions detailed in the "European ATM Master Plan - Roadmap for the safe integration of drones into all classes of airspace" (SESAR Joint Undertaking, 2020a). U-space constitutes a group of new services based on highly digitalized and automated operations and procedures. The primary objective of U-Space is to support flight safety and secure and efficient access to airspace for several UASs. Therefore, U-space is a favorable framework designed to facilitate any type of routine mission in all categories of airspace and all types of environments, even for those with very dense traffic, providing an appropriate interface for manned aviation and air traffic control (SESAR Joint Undertaking, 2017). By taking into account the U-space needs, the most recent developments in technology, such as AI, IoT, and the fifth generation (5G) mobile networks, will be used, considering the requirements related to cybersecurity as well as the security and privacy of citizens and the protection of the environment.

In the context of U-space, the following three services have already been defined as "essential":

- **Electronic (e)-registration**: According to the existing European regulations (European Aviation Safety Agency, 2018; European Commission, 2019), e-registration is mandatory for all UAS operators, except in cases where UAVs have a maximum total take-off weight of less than 250 g as well as for certain categories of UAVs used in the open category.
- **Electronic (e)-identification**: Electronic identification allows authorities to identify a flying unmanned vehicle and link it to the information stored in the register. This identification serves safety, flight safety requirements, and law enforcement procedures.
- **Geo-Awareness** (geo-fencing, geo-aging, and geo-restriction): The term "geo-awareness" describes the development of the ability to perceive space and create access restrictions ("fencing") for an unmanned aircraft by defining specific areas into which it does not enter based on its software and/or hardware design, even if the operator intentionally or unintentionally instructs the drone to enter those areas. The EU regulatory framework (European Commission, 2021a; European Aviation Safety Agency, 2018; European Commission, 2019) provides recommendations for geo-awareness along with other features in the design of drones, thus providing regulations for the development of "geofencing" (Eurocontrol, 2018a).

According to SESAR Joint Undertaking (2017), the basic principles on which U-space will be based to support safe, efficient, and high-level flight safety access of several UASs to airspace are briefly described as follows:

- Flight and ground safety.
- Scalability and flexibility.
- Automation under control.
- Equality and justice.
- Competitiveness and efficiency.
- Use of the existing infrastructure.
- Adoption of new technologies.
- Risk and performance assessment.

The evolution of U-space relies on the gradual availability of groups of enabling services and technologies, which will advance as the drone's level of automation improves, and advanced technologies for interaction with the environment and other aircraft (manned and unmanned) are enabled, primarily through digital information exchange. The four groups of services (Fig. 1) described in SESAR Joint Undertaking (2017) are briefly described below:

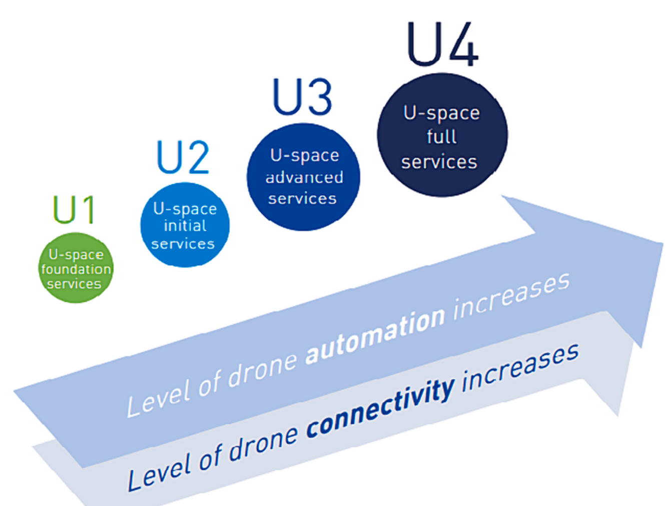

Fig. 1. U-space service groups (source: U-space Blueprint) (SESAR Joint Undertaking, 2017).

- **U1 — U-space foundation services**: These methods include e-registration, e-identification, and geofencing.
- **U2 — U-space initial services**: Management of the operational support for drones. Flight planning, flight authorization, tracking, dynamic airspace information, and procedural interfaces with air traffic control may also be included.
- **U3 — U-space advanced services**: They support more complex operations in dense traffic areas and may include airspace capacity management and collision-detection assistance.
- **U4 — U-space full services:** Specific services that provide integrated interfaces with manned aviation. Based on the very high level of automation, connectivity, and digitalization of both drones and the U-space systems, the full operational capability of the U-space is supported.

In April 2021, the EU adopted and published a policy package for regulating U-space, which consisted of three implementation regulations whose new provisions have been in force since January 26, 2023. This regulatory package consists of regulations 2021/664 (European Union Aviation Safety Agency, 2022), 2021/665 (European Commission, 2021b), and 2021/666 (European Commission, 2021c). In addition, on December 16, 2022, the EASA published the first edition of the Acceptable Means of Compliance and Guidance (European Union Aviation Safety Agency, 2022) to assist in the implementation of the above regulatory package.

Related U-space research projects

SESAR JU completed the first wave of 19 U-space projects in 2019, that demonstrated U-space services from U1 to U3 in various environments. The report on the consolidated SESAR U-space research and innovation results (SESAR Joint Undertaking, 2020b) concluded that U1 and U2 services are essentially ready for use in rural areas, segregated airspaces, and low-density airspaces. A complete description of the results of the projects can be found in Annex 2 of SESAR Joint Undertaking (2020b). The CORUS consortium brought together experts from aviation (manned and drone), research, and academia, guided by a 21-member stakeholder advisory board, to develop a harmonized approach for the integration of drones into a very low-level (VLL) airspace, including the airspace around airports. The CORUS consortium developed a CONOPS for the U-space, proposing an initial architecture for this airspace with a detailed definition of the airspace types to be used for VLL drone operations and their services such that operations are safe and efficient. The activity of the CORUS project centered around three workshops, wherein a new iteration of the CONOPS is discussed in each workshop, allowing the project to refine and validate them, leading to the third edition of U-space CONOPS (SESAR Joint Undertaking, 2019), providing the latest baseline for U-space services. In parallel with CORUS, several technological (e.g., DREAMS, IMPETUS, CLASS, and TERRA) and demonstration (e.g., PODIUM, GOF, and SAFEDRONE) projects have been launched to test and develop new technologies and services for U-space (Barrado, et al., 2020).

CORUS-XUAM (Extension for urban air mobility) was proposed by the consortium that delivered the CORUS U-space CONOPS in 2019 (SESAR Joint Undertaking, 2019), which was extended by the addition of urban air mobility (UAM) expertise. CORUS-XUAM is a recently completed 2-year very-large-scale demonstration project designed to show how U-space services and solutions can support integrated UAM flight operations, allowing electric vertical take-off and landing (eVTOL) UASs and other airspace users (unmanned and manned) to operate safely, securely, sustainably, and efficiently in a controlled and fully integrated airspace without undue impact on operations currently managed by the ATM. The CORUS-XUAM project developed the latest edition of U-space CONOPS (fourth edition) (SESAR Joint Undertaking, 2023), which now encompasses urban air mobility, extends the previous edition, and:

- addresses UAM needs, particularly processes at vertiports, airspace structures, and flight rules, and eVTOL passenger-carrying ops,
- is aligned with the EU's U-space regulations, and
- includes inputs from other SESAR research and innovation projects.

The X-TEAM D2D project has been funded by the SESAR 2020 Exploratory Research ER4-2019 Call. The high-level aim of the X-TEAM D2D project (SESAR Joint Understaking, 2021a) is to define, develop, and initially validate CONOPS supporting the seamless integration of ATM and air transport into an overall intermodal network, including other available transportation means (surface and water), to contribute to enabling door-to-door connectivity in 4 h between any location in Europe, in compliance with the target assigned by the ACARE SRIA FlightPath 2050 goals (Directorate-General for Mobility and Transport and Directorate-General for Research and Innovation, 2011). The target CONOPS, provided and initially validated by the X-TEAM D2D project, encompasses both transportation platform integration concepts and innovative seamless mobility as a service, including the ATM concepts. The developed CONOPS will be also preliminarily evaluated against the existing and specifically defined applicable key performance areas and key performance indicators, implementing both qualitative and quantitative performance assessment approaches (SESAR Joint Undertaking, 2021b).

The aim of the ASSURED UAM project (European Commission, 2021d) is to support cities in the process of launching unmanned operations and their integration within urban transport systems by providing local government units, decision makers, and other interested parties with recommendations on UAM. The process of integrating urban vertical mobility requires several adaptations in the field of public transport management, including logistics of operations and deployment of dedicated infrastructure. The ASSURED-UAM project aims to support these adaptations by providing a multidisciplinary study of operational and policy frameworks for the introduction of unmanned modes of UAM (Dziugiel et al., 2022). Deliverable D1.1, titled "Technology readiness review," (European Commission, ASSURED UAM, 2021) aims to identify and describe the development paths and factors for the most appropriate technology solutions expected to shape the future UAM, with reference to the three time horizons considered in the ASSURED UAM project.

PJ34 AURA project and Eurocontrol

The primary mission of Eurocontrol is to support European aviation by providing technical excellence and civil–military expertise across the entire spectrum of ATM, ensuring the safe integration of UASs while ensuring that the rights of all airspace users remain unchanged. Eurocontrol developed the ATM UAS integration operational concept (Eurocontrol, 2018b) that complements the corresponding EASA operational concept (CONOPS) (European Aviation Safety Agency, 2015). Moreover, EUROCONTROL develops safety scenarios, executes simulations assessing the flight safety of UAS operations, and communicates the complexity of integration.

The PJ34-W3 AURA is an EU-funded project aimed at easing the introduction of new actors into the existing and future air traffic environments (SESAR Joint Undertaking, 2021b). The AURA project sets the conditions for U-space information exchange with ATM via system-wide information management (SWIM) and ratifies a set of specific U-space services by establishing a service definition for candidate SWIM services. Second, it defines a new Cooperative ATM-U-space Operations Concept for UASs in a fully cooperative environment with ATM that extends beyond the existing concepts developed for U-space and validates these new concepts. The AURA project contributes to the development of VLL markets, enabling the introduction of new agents in a secure, harmonized, sustainable, and efficient manner that is compatible with the current ATM environment. The project also contributes to avoiding airspace segregation and increasing interoperability (SESAR Joint Undertaking, 2021b).

USA — UTM

In the US, the Federal Aviation Administration (FAA) and National Aeronautics and Space Administration (NASA), as well as major industries, work together to explore the concept of operation, data exchange requirements, and a regulatory framework that will allow multiple applications of UASs in the line of sight and at low altitudes below 400 ft above the ground level (AGL) (Federal Aviation Administration, 2018). These are planned for airspaces in which no air traffic services are provided by the FAA. According to the FAA and NASA, a UTM System is a "traffic management" ecosystem (Fig. 2) for uncontrolled operations that is separate from the ATM system of the FAA. The development of UTM will ultimately define the services, roles and responsibilities, information architecture, data exchange protocols, software functions, infrastructure, and performance requirements to enable the low-altitude management of uncontrolled aircraft. With UTM (Federal Aviation Administration, 2019), as envisioned by US federal agencies, there will be a collaborative interaction between unmanned aircraft operators and the FAA to determine and relay the airspace status in real time. The FAA provides real-time restrictions to drone operators who are responsible for managing their activities safely within those restrictions but without receiving air traffic control services from the FAA. The primary means of communication and coordination between the FAA, drone operators, and other stakeholders is envisioned to be a distributed network of highly automated systems via application programming interfaces (APIs) rather than face-to-face communication between pilots and air traffic controllers.

In 2018, the FAA's Office of NextGen published an initial general CONOPS (ConOps: Concept of Operations, version 1.0) of UTM, which presents the vision and describes the associated business and technical requirements for developing a supporting architecture and operations within an ecosystem. In this regulation, UTM is defined as the approach in which the FAA supports unmanned aircraft operations flying at low altitudes. UTM exploits the ability of the industry to supply services under the FAA's regulatory authority in areas that are currently lacking. It is a community-based traffic management system in which remote pilots and operators providing operation support services are responsible for coordinating, executing, and managing operations in accordance with the air traffic rules established by the FAA. This unified set of services enables collaborative operation management among UAS operators, facilitated by third-party support providers, by sharing information through appropriate networks.

UTM CONOPS version 2.0 (Federal Aviation Administration, 2020) continues to focus on UTM operations below 400 ft AGL and also addresses increasingly complex operations both within uncontrolled and controlled airspaces and from one to the other. The 2η version enlarges the operational scenarios set, with improved elements, describing complicated operations in denser airspace, including BVLOS operations in controlled airspace. It also includes updated descriptions/approaches for various UTM elements, including reserved areas (airspace volumes) for UASs, performance authorizations, data archiving and access, categories of services provided by UAS service suppliers (USS), UTM/ATM emergency notifications, and safety issues related to UTM operations. New topics that are also initiated in UTM ConOps 2.0 are airspace authorization for BVLOS flight within controlled airspace, UTM architecture support for remote UAS operator identification, and efforts to develop standards within the industry as an integral part of enabling UTM functions (Federal Aviation Administration, 2020).

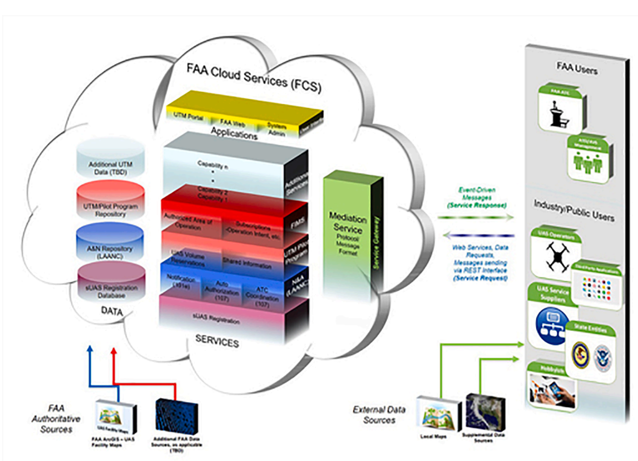

Fig. 2. FAA's UTM ecosystem (Source: https://www.faa.gov/).

Pilot programs and UTM technical capability levels

The UTM CONOPS version 2.0 of the FAA (Federal Aviation Administration, 2020) supports a spiral implementation approach in which the initial concept matures through the analysis of more complex airspace environments that have been tested and validated through field testing, including testing within the FAA's UTM pilot program (Federal Aviation Administration, National Aeronautics and Space Administration, 2021), the FAA's UAS integration pilot program (Federal Aviation Administration, 2017), and NASA's UTM technical capability level (TCL) (Rios et al., 2020; Aweiss et al., 2019; Homola et al., 2019). As part of the TCL-4 flight tests, five sets of flight tests were conducted over a period of 5 years, demonstrating TCLs with different environmental complexities, airspace constraints, and operational objectives. As an example of these TCL differences, the early flight tests (TCL-1) (Rios et al., 2020; Aweiss et al., 2019) focused on a single "small" UAS (sUAS) flying in unconstrained airspace, within the pilot's field of view and over unoccupied open space (Johnson et al., 2017). Later, TCL-4 flight tests demonstrated multiple operations of small UASs facing airspace restrictions and limitations in densely populated downtown locations. The TCL-4 demonstration (Rios et al., 2020) in Texas resulted in more than 400 data-collection flights using eight real UASs, 15 simulated vehicles, nine flight crews, and six UAS service providers. The TCL-4 was designed to demonstrate five scenarios, creating various sets of UAS events and activities. These scenarios focused on a variety of potential events and issues, such as an oncoming weather front, shared airspace, USS failure, and multiple vehicles experiencing communication, navigation, and surveillance problems. The results of these tests are presented in (Homola et al., 2019).

UK — Open-access UTM

The Department for Transport (DfT) commissioned the Connected Places Catapult (CPC) to develop and test an open-access UTM framework to demonstrate an option for the expanding drone sector of the UK to coexist with other forms of aircraft. This project was designed to facilitate further research and demonstration activities within the future flight challenge (Connected Places Catapult, 2021). In collaboration with the DfT, the CAA and industry stakeholders developed a national UTM framework called Open-access UTM. Open-access UTM has successfully progressed from concept to live field trials, demonstrating how UTM could deliver ATM services in the future.

Among the fundamental principles set out at the CAP 722 "Unmanned Aircraft System Operations in UK Airspace — Policy and Guidance" (UK Civil Aviation Authority, 2022), civil UAS operating in the UK must satisfy at least the same safety and operational standards as manned aircraft when conducting the same type of operation in the same airspace. As a result, compared with manned aircraft operations of an equivalent class or category, UAS operations must not present or create a greater risk to the safety of persons, property, and vehicles on the ground as well as to aviation safety for all flying vehicles. Regarding unmanned aircraft, the type of operation being conducted is the key element rather than the owner or the purpose of the operation. By considering that the aircraft is "unmanned," the incident outcomes or accidents are only dependent on where the incident/accident occurred. Consequently, the CAA focuses on the risk that the UAS operation presents to third parties, meaning that more effort or verification is required when the risk is greater.

The operating principles are similar to those established by the EU and primarily include visual line of sight (VLOS) operations, BVLOS operations, avoidance of other aircraft, and protection of third parties, uninvolved persons, and congested areas. The "1:1 rule" is an easy-to-remember rule that can be used to determine when and the amount of the minimum separation distance from uninvolved individuals may need to be increased. This is based on the relationship between the height of the unmanned aircraft and its distance from the uninvolved person (1:1 line). The horizontal distance between the unmanned vehicle and non-involved people on the ground should not be less than the height of the aircraft. The categories of UAS operations are similar to those given by the EU and are classified based on the level of risk posed by each operation. This "risk and operation-centric" approach means that each operation will fall into one of the three operating categories (open, specific, and certified categories).

Russia — Russian UAS traffic management (RUTM)

The legal basis for the use of the airspace of the Russian Federation and activities in the field of aviation (Serebryakov et al., 2023) as well as the general procedure for performing civil, state, and experimental aviation (EA) flights in the airspace of the Russian Federation are established by a number of regulatory legal acts, the key of which is the Air Code of the Russian Federation (issued on March 19, 1997; No. 60-FZ) (Serebryakov et al., 2023). The rules governing the legal status of UAVs emerged when the Federal Law (December 30, 2015; No. 462-FZ) "On Amendments to the Air Code of the Russian Federation regarding the use of UAV" was implemented. In May 2019, the Government of the Russian Federation, by its decree number 658 of May 25, 2019, endorsed the "Rules for Accounting Unmanned Civil Aircraft" with a maximum take-off weight ranging from 250 g up to 30 kg made in Russia or imported. This document applies to the most common unmanned civil aircraft, known publicly as "drones," including those used by individuals for recreational purposes. According to the decree, drone owners are not allowed to fly them without undergoing a registration procedure (Alekseychuk, 2019). Regulatory issues in the field of UASs are a shared responsibility among different entities (Serebryakov et al., 2023) in the Russian Federation, such as a commission under the President of the Russian Federation, a governmental Commission for Transport, an interdepartmental Working Group as well as Association of Employers and Enterprises of the Industry of Unmanned Aerial Systems, named "AERONEXT" which works in the framework of the "ANO CENTER AERONET" ("АНО ЦЕНТР АЭЭРОНЕТ") Working Group of the (Russian) National Technology Initiative.

The issue of integrating UASs into the common airspace of the Russian Federation is reflected in the proposals and the road map, described in the "Conceptual proposals for the integration of unmanned aviation systems into the airspace of the Russian Federation" developed by the AERONET. The anticipated result of the roadmap actions is the development of a regulatory and technological structure for the integration of UAS; the expansion of UAS air navigation capabilities; the application of conditions for flexible, risk-based, and performance-based access of UASs of all classes and categories to Russian airspace; and the implementation of UAS in numerous areas of the economy and daily life of the country. The primary objectives set out in the roadmap (Nti-aeronet.ru, 2018) are as follows:

- Guaranteeing safe operation and effective commercial UAS applications in Russian airspace.
- Limiting regulatory constraints regarding the development of a new mass market for the civilian use of UASs.
- Shortening the gap between Russia and other countries, particularly the USA and EU, in relation to organizing UAS air traffic and creating new technologies and competencies in this area.
- Harmonization of UAS regulations in the area of air navigation services, development, certification, and safe operation of UASs is based on international standards, recommendations, rules, and procedures.

As stated in Nti-aeronet.ru (2018), the roadmap development will be implemented at different stages from 2019 to 2035 and beyond. The specific services by stage and category are described in Russian in a table presented in Nti-aeronet.ru (2018) (p. 95) and in English by Serebryakov et al. (2023) (p. 7) and are summarized as follows:

- **Step 1 (2019–2020):** The preparatory period for the integration of UAS flight operations into Russian airspace, which includes VLOS flights in designated areas of uncontrolled airspace and BVLOS flights in segregated airspaces. Several technologies and services should also be developed, such as remote identification, base communications, navigation and surveillance, basic DAA, as e-registration of UAS pilots, e-identification, and pre-tactical geofencing (Nti-aeronet.ru, 2018).
- **Step 2 (2021–2025) —** Initial integration of UAS flight operations into Russian airspace: Transition period from segregated UAS flight operations to joint flights with manned aircraft in a nonsegregated airspace. Development of command and control (C2) satellite lines, enhanced communications, navigation, surveillance, advanced DAA, low-altitude traffic organization system of UASs, and tactical geofencing. Strategic conflict resolution and procedural interactions with ATM are envisaged (Nti-aeronet.ru, 2018).
- **Step 3 (2026–2030):** UAS integration into nonsegregated Russian airspace, including BVLOS flights in controlled and uncontrolled airspaces under conditions of established restrictions. Further development of integrated C2 and DAA, a system of organization of low-altitude traffic DAA, integration with ATM, dynamic geofencing, tactical conflict resolution, dynamic bandwidth management, and joint work with ATM (Nti-aeronet.ru, 2018).
- **Step 4 (2031–2035) —** Advancement and enlargement: Perform a large number of UAS flights in all classes of airspace coexisting with manned aircraft based on the provision of advanced and expanded internal rules (Nti-aeronet.ru, 2018).

China — UAS operation management system

China is creating a concept for UAS operations management known as the UAS operation management system (UOMS) (Civil Aviation Administration of China, 2015). UOMS will involve multiple vendors to provide aircraft registration, alerts, or location services. This initiative aims to incorporate the UOMS into the existing ATM systems and develop a competent system for general aviation. An interface between a cloud containing all drone flight information and UAS operations is one of the tasks performed for its development. Moreover, numerous tests have been conducted to evaluate UOMS information systems and their coordination with general aviation systems as well as trials with large UASs (Civil Aviation Administration of China, 2018).

China used its leading UAS design and manufacturing capability to support the Civil Aviation Administration of China (CAAC) in performing UAS pilot programs and the trial operation of specific types of UASs. Simultaneously, the CAAC sets up and continuously improves the related UAS standards and regulations through pilot handling experience. During the 41st session of the ICAO Technical Commission Assembly (August 2022 (International Civil Aviation Organization, 2022)), China announced that more than 10 UAS regulatory documents, 22 Chinese national standards, five civil aviation industry standards, and 116 group standards covering operations, manufacturing, airworthiness, and other fields are in effect. Based on the regulations and standards in the field of civil unmanned aircraft, a scientific body was formed according to their internal connections and the framework of regulations and standards for UASs. The establishment of the "Regulatory and Standard System for Civil Unmanned Aviation in China" is the foundation and premise for guiding the standardization of civil UASs and the construction of the standard system. Furthermore, it forms the basis for compiling standards, revising plans, and programming. The standard system contains a blueprint of the existing, due, and expected standards and is a standard system model. Since 2018, the CAAC has gradually condensed and formed a framework of regulations and standards for civil UAS based on preliminary research and has been continuously revised and improved.

In May 2023, China published its "Interim Regulations on the Management of Unmanned Aircraft Flights" (will be implemented in January 1, 2024) (Civil Aviation Administration of China, 2023) for the purpose of regulating the flight of unmanned aircraft and related activities, promoting the healthy and orderly development of the unmanned aircraft industry and maintaining aviation safety, public safety, and national security. UAVs are classified into micro, light, small, medium, and large categories according to their performance indices. The national air traffic management leading body will lead the national unmanned aircraft flight management in a unified manner and organize and coordinate the resolution of major problems in the management of unmanned aircraft.

During the first EU–China Aviation Partnership Project Drone Workshop, (6–8 June 2018 Shenzhen, China) the CAAC ATM Engineering Technical Research Institute representative presented some of the basic principles of the UOMS (Butterworth-Hayes, 2019). According to the presentation of information exchange between the General Aviation Flight Service (GAFS) and the UOMS should be based on the principle of "complete exchange," meaning that the GAFS should transmit all general aviation flight plans and real-time flight data to the UOMS while the UOMS should transmit all flight plans (except open operations) received by UOMS and real-time UAS flight data to the GAFS. Regarding the interconnection of the UOMS with the ATM system, the current ATM should communicate the flight path of the manned aircraft approaching the terminal control area with the UOMS to provide the basis for the required task clearance and real-time collision risk alert for the UOMS. Because of physical isolation, the ATM does not need to broadcast the en-route flight paths of commercial flights. The UOMS should broadcast all flight plans (except open operations) received by the UOMS to the ATM and real-time UAS flight data, such as real-time latitude and longitude, speed, heading, and altitude flight identification codes. Future research to progress the development of the UOMS network includes drawing up standard specifications for the data interface between the U-cloud, where drone flight information is stored, and UAS operations and developing a geofencing system that will be built into the flight control system based on real-time kinematics high-precision positioning techniques.

Japan — Japan unmanned system traffic and radio management consortium

The voluntary "Study Group for Control Systems for the Safe Operation of Drones" was set up in 2015 and has conducted research and disseminated information on the necessary measures for the social implementation of drones and other unmanned vehicles and the type of social infrastructure that needs to be developed. As a continuation, another group was established, called "Japan Unmanned System Traffic and Radio Management Consortium" (JUTM), which acts as an executive body to support the implementation of various measures relating to unmanned vehicles and promote their commercialization. The goal of the JUTM is the social application of unmanned vehicles (Japan Unmanned System Traffic Radio Management Consortium (JUTM), 2023).

To promote their use in all types of industries, JUTM studies the safe, reliable, and smart operation of unmanned vehicles by considering several factors such as technology, systems, and business, and promoting activities to develop an appropriate environment. They are working towards a future vision, which includes the realization of "a future society where people and drones can co-exist" and strive to create innovative business models that use unmanned vehicles and spread them worldwide, thereby contributing to the enhancement of the international competitive strength of Japan.

JUTM conducted flight demonstrations to test UTM concepts in March and October 2017 (namely, the Demo) in the Fukushima Prefecture, Japan, to accelerate discussions to build a UTM by simulating the environment with several sUAS operations in airspace, test communications between the operators and the JUTM UTM system, and obtain data on operators' behavior for an early UTM concept (Nakamura et al., 2018). A total of 44 organizations participated and approximately 120 flights were fabricated with 20 small unmanned aircraft, including one simulated aircraft. The concept of UTM that JUTM considers is similar to the basic UTM services of NASA UTM (Rios et al., 2016). However, the Demo was created with limited time and resources; hence, the measures were not always optimized and may not reflect the future.

Research in unmanned traffic management systems

In addition to the above international and national frameworks and concepts, the research community has conducted extensive studies to provide guidance for safe UAS operations from either the technological or regulatory perspective. Summaries of these efforts include but are not limited to the following reviews: concerning UAS command, control, and communication technologies and examination of technologies supporting both VLOS and BVLOS UAS operations (Stansbury et al., 2009). For each, data link technologies, flight control, and air traffic control coordination were considered, and the existing protocols and standards for UAS and aircraft communication technologies were discussed.

Regarding the DAA, a group of researchers at Iowa State University, USA (Brittain and Wei, 2019) developed a deep multi-agent reinforcement learning framework capable of identifying and resolving disputes between flying vehicles in a condensed, stochastic, and dynamic en-route sector with multiple merging points. The proposed framework utilizes an advantage actor–critic model that incorporates the loss function from proximal policy optimization to stabilize the learning process. In addition, they used a centralized learning and decentralized execution scheme, in which one neural network was learned and shared by all agents in the environment. They highlighted that the key challenge in managing low-altitude and urban air mobility traffic is to provide real-time advisories to aircraft to ensure safe separation along both air routes and at the intersections of these air routes. The results showed that, in extremely condensed air traffic scenarios, the proposed framework could resolve 99.97 % and 100 % of all conflicts at intersections and merging points, respectively.

Furthermore, Yu and Zhang (2015) presented an overview of the progress in sense and avoid (S&A) technologies in the sequence of fundamental functions/components of S&A in sensing techniques, decision-making, path planning, and path following. A taxonomy of conflict detection and resolution approaches for operating UAVs in an integrated airspace was proposed by Jenie et al. (2017). Possible approaches to UAVs were surveyed and broken down based on their types of surveillance, coordination, maneuvering, and autonomy.

Regarding the UTM architecture, Labib et al. (2019) evaluated the potential shortcomings of the existing centralized UTM and U-space service architectures in favor of a more distributed approach based on low-altitude airspace configured as a multilayer network incorporating nodes and airways. They assessed optimal pathfinding by examining three heuristics: static path planning, global probabilistic dynamic, and local pheromone-guided heuristics. They reported that the local pheromone-guided heuristic outperformed the global probabilistic dynamic heuristic in handling high levels of drone traffic. Acevedo et al. (2019) explored four-dimensional (4D) airway modeling and conflict detection and proposed a method based on the representation of the airspace as a 4D grid of cells. Considering a set of UAVs with their planned 4D trajectories (flight plans), the entire scenario was discretized as a 4D grid that solved the problem by filling the appropriate cell for each waypoint from the paths and checking the neighboring cells.

The drone information service demands for enabling safe drone operation in a VLL airspace were examined in the SESAR Horizon 2020 funded project (DREAMS) (Doole et al., 2018), with an emphasis on the urban environment. The researchers also conducted a gap analysis of existing information services from manned aviation and current U-space service providers, in line with drone operators and user requirements. This research highlighted the critical present-day shortcomings relevant to the implementation of urban UTMs, including drone traffic activity and flow management. Lundberg et al. (2018) have identified second-order issues or side effects that occur when using basic UTM tools such as geofencing and DAA in strongly simulated random point-to-point city traffic. They concluded that more advanced UTM tools are required to support the optimization and automatic computation of airspace solutions.

The ASSURED-UAM project evaluated the existing and prospective technologies that could support UAM. Overall, UAM-enabling technologies have reached a good level of maturity (European Commission, ASSURED UAM, 2021) owing to the possible exploitation of technologies already being considered in the domain of unmanned aerial systems; however, the technology is not sufficiently developed to allow the immediate implementation of unmanned aerial systems in the market. The ASSURED-UAM project evaluated the existing and prospective technologies that can support UAM, such as propulsion, thrust, and lift design configurations; powertrain technologies; and information and communication technologies (ICTs), including the IoT, communication technologies (5G and beyond), Big Data processing, and smart cities concept (European Commission, ASSURED UAM, 2021). The primary results of these activities related to the aforementioned technologies are presented by Di Vito et al. (2023).

To achieve a multimodal transport system, the X-TEAM D2D project researchers have emphasized the importance of investing in communication systems to enable the exchange of data between the modes (SESAR Joint Undertaking, 2021b). This will be the main driver for achieving progress towards more efficient and sustainable transportation in the future. In the field of European policy/mobility, net-zero emission technologies, digitalization in transport, and algorithmic governance will enable the domination of automated/autonomous mobility in almost all modes of transport, leading to significant progress in operational efficiency (SESAR Joint Undertaking, 2021b). In the European policy/ICT area, access to data, algorithmic governance, and policy strongly support the development of ICTs. In particular, IoT, 6G, and beyond, Big Data, and the concept of the smart city are expected to address all regulatory hurdles. The increasing complexity of future systems requires a new approach for managing such systems. Computer-readable algorithmic governance that enables orchestration at the regulatory level is implemented as a critical component of digitally integrated urban and suburban transport systems (SESAR Joint Undertaking, 2021b). The barrier to implementing algorithmic governance to ensure efficient high-level management of air transportation as well as integration with other modes of transport are addressed within a limited scope by AgentFly Technologies (AgentFly Technologies, 2024). The company offers solutions (trajectory planning in 4D, geofencing, avoidance of no-flight zone, and other traffic for operational safety) for algorithmically assisted services of UAS mission planning and execution only within the VLL airspace (small UAS, unintended for traveling purposes). However, passenger flights, large cargo operations, and integration with other transport modes are not supported.

Research related to artificial intelligence-based unmanned aerial vehicle navigation

There has been significant research interest in autonomous UAV navigation, particularly in allowing UAVs to fly and perform their operations according to the environment. The integration of AI into autonomous UAV navigation is considered an important element that demonstrates the significant role of AI in providing fundamental human control characteristics to vehicles. Rezwan and Choi (2022) presented a comprehensive survey of different AI approaches for autonomous UAV navigation, categorized as optimization- and learning-based approaches.

Optimization-based approaches cover the traditional mathematical-based problem-solving algorithms of AI, which, even though they are quite complex in terms of time and space, can achieve near-optimal solutions for any given nondeterministic polynomial-time hard (NP-hard) problem (Rezwan and Choi, 2022). The most widely used optimization-based AI approaches for autonomous UAV navigation are discussed below.

Particle swarm optimization (PSO), introduced by Kennedy and Eberhart (1995) in 1995, is a population-based search algorithm that simulates different animal groups. In UAV navigation, PSO considers UAVs as particles and controls their movement in three-dimensional (3D) space. An improved version of offline UAV navigation while avoiding obstacles was presented by Jalal (2015). The modified PSO (MPSO) functions similarly to conventional PSO, where an additional error factor is modeled to ensure convergence. The main function of the error factor is to convert the infeasible paths generated by the PSO into feasible paths. MPSO repositions and reinitializes the particles included in an obstacle boundary for confirmed optimization. Another modified version of PSO was presented by Phung et al. (2017), where the conventional continuous PSO was modified into a discrete PSO to solve the UAV path-planning problem. The authors modeled the UAV path-planning problem as a traveling salesman problem while considering discrete 3D space and obstacles.

Ant colony optimization (ACO) was proposed by Colorni et al. (1991) to solve NP-hard optimization problems. They proposed a novel approach to distributed problem–solving and optimization based on the results of low-level interactions among many cooperating simple agents that are not aware of their cooperative behavior. Their work was inspired by the study of ant colonies, in which each ant performs very simple actions and does not explicitly know what the other ants are doing. For autonomous UAV navigation, a multi-colony ACO-based solution that avoids obstacles in 3D space was proposed by Amer et al. (2021). The goal of this research was to implement obstacle avoidance UAV path planning using the multi-colony ACO algorithm. They experimentally investigated the use of the multi-colony ACO approach resulting from effective path planning for UAVs compared with a single-colony ACO approach. According to the authors, multi-colony ACO overcomes the premature convergence problem caused by single-colony ACO.

A **genetic algorithm (GA)** was implemented by Bagherian and Alos (2015) to solve the NP-hard problem of UAV navigation. In the first stage, the 3D position was encoded into chromosomes consisting of acceleration, climbing angle rate, and heading angle rate at distinct UAV time instances. This chromosome was decoded to obtain the 3D coordinates at the next time-instance for the UAV. The 3D coordinates were then evaluated using a fitness function that considered the costs of the distance between two points, total path length, height, and obstacles. A hierarchical recursive multi-agent GA (HR-MAGA) approach was proposed by Yang et al. (2020). During the evolution process of the HR-MAGA, agents can detect the environment, communicate with their neighbors, and decrease their loss by employing corresponding operators who discover a good solution instantaneously. Moreover, the HR-MAGA can optimize the local path to obtain a more refined path using a hierarchical recursive process.

Dijkstra's algorithm was developed in 1956 by the computer scientist Edsger W. Dijkstra and was published after 3 years. It is a weighted graph method that calculates the shortest distance between two nodes and can be employed in a variety of applications, including navigation (Dhulkefl et al., 2020). A starting point was chosen in Dijkstra's algorithm and all other nodes were regarded as infinitely distant. When nodes are approached, their distances are updated. Dijkstra's algorithm examines the neighbors leaving a node at each step; if a shorter path is discovered, the distances are updated.

The A* algorithm is a hybrid of Dijkstra's algorithm, which combines the information used by Dijkstra's algorithm (favoring vertices near the beginning point) with the information used by the greedy best-first search (favoring vertices close to the target). Although Dijkstra's and A* algorithms are more complex than other optimization-based approaches, related studies (Ghambari et al., 2020) have proposed different modified versions of these algorithms that consider target tracking and real-time updates of the environment to implement obstacle avoidance for autonomous UAV navigation.

Learning-based approaches offer very low complexity and can achieve near-optimal solutions to any NP-hard problem. The most widely used learning-based AI approaches for UAV navigation are reinforcement learning (RL), deep learning (DL), asynchronous advantage actor–critic (A3C), deep reinforcement learning (DRL) using the Markov decision process (MDP), partially observable MDP, and convolutional neural networks (CNNs).

RL is an effective and widely used AI technique that learns the environment by performing various actions and determining the optimal operating strategy. The agent and environment, which are the two fundamental components of RL, use the MDP to interact and determine which action to take (Ponsen et al., 2009). AlMahamid and Grolinger (2022) have classified and discussed RL algorithms based on the environment, algorithm characteristics, abilities, and applications in different UAV navigation problems, which is helpful in selecting appropriate RL algorithms for UAV navigation.

A3C is an advanced DRL algorithm in which each agent consists of two networks: actor and critic networks. A3C is commonly used in multi-agent environments; therefore, it is highly efficient in multi-UAV scenarios. Wang et al., (2021a, 2021b) proposed an A3C-based DRL framework for autonomous UAV navigation to support mobile-edge computing. Each UAV consists of critic and actor networks. All actor networks in the UAVs were trained using the same data from the entire network; however, critic networks were trained using individual UAV data with a multi-agent DDPG.

DL is a common tool for vision-based UAV navigation that includes only the deep neural network (DNN) part of the DRL. Different types of DNNs, such as fully connected neural networks and CNN, can be used to achieve autonomous navigation of UAVs in extremely difficult environments. Amer et al. (2021) presented an approach to autonomously navigate UAVs on predefined courses using only visual images from an embedded onboard camera, exploiting a deep CNN combined with a regressor to output drone steering commands. Related research performed by Menfoukh et al. (2020) evaluated an approach for automatic trail management within a forest trail environment was presented. In the proposed approach, a DNN was optimized to upgrade forest path detection in the direction of UAVs using images with sufficiently high resolution that are representative of the UAV platform.

Comparison of concepts

CONOPS development in the EU follows a progressive approach that focuses on specific challenges while simultaneously being supported and demonstrated by various projects (ICARUS, BUBBLES, DACUS, AMULED, etc.). The CORUS project (2017 to 2019) produced the third edition of the U-space CONOPS in October 2019, proposing an initial architecture for this airspace with a detailed definition of the airspace types to be used for VLL drone operations and their services such that operations are safe and efficient. A preliminary version of the fourth edition of the CONOPS (3.10) was released in July 2022 for comments, and a consolidated fourth edition was produced by the CORUS-XUAM project and published in July 2023. The fourth edition includes improved consideration of UAM needs, adjustments according to regulatory evolution, and the incorporation of inputs stemming from other research and development projects. Deliverable D1.5 of the ASSURED UAM (ASSURED UAM, 2022) project aimed to define CONOPS for the integration of UAM into urban and *peri*-urban environments, with reference to the three time horizons (5, 10, and 15 years) considered in the ASSURED-UAM project. Finally, the X-TEAM D2D project focused on a detailed consideration of ConOps for ATM integration in intermodal transport networks serving urban and extended urban (up to regional) mobility, considering the transportation and passenger service scenarios envisaged for the next decades according to baseline (2025), intermediate (2035), and final (2050) time horizons (SESAR3 Joint Undertaking, 2023).

Regarding the initiatives of international organizations and by comparing the approach of the US, the EU, Russia, and China in relation to the ICAO regulatory framework, we can observe homogeneity in the fundamental principles that focus on maintaining flight and ground safety, a flexible and scalable structure, equity and fairness, automated communications, and the use of existing infrastructure. Of note, all national and international regulatory bodies aim to ensure the safety of manned aviation and avoid disruption to the normal airflow of manned aircraft. In this context, the lack of the human factor, which, despite the high levels of automation of modern civil aircraft, has the ultimate and sole responsibility for collision avoidance, is critical. In view of this critical factor, technologies that will support the functions of detection, tracking, and collision avoidance, primarily of noncooperative entities, are considered fundamental to the realization of integrating drones into air traffic control.

There is also a common understanding in all frameworks concerning the harmonized development of standards, regulations, and common protocols to reduce risks and maintain stability. The need for interoperability based on common standards and regulations is also recognized in both Western (US and EU) and Eastern (Russia and China) regulatory frameworks and concepts. In this context, the EU–China Aviation Partnership Project (Butterworth-Hayes, 2019) was established and successfully operated for 5 years (2016–2021) and will continue for another 3 years. The basic conceptual approach (Civil Aviation Administration of China, 2015) by Russia clearly includes the requirements to normalize differences and harmonize the Russian concept with those in the EU and the US.

Another important area of common understanding is communication, in which all approaches recognize the need to move from a human-centric system to a machine-to-machine (M2M) system. In the existing ATM system, communication for smooth traffic flow and flight and ground safety ultimately depends on pilots and air traffic controllers, and all regulators prescribe a transition to a fully automated system based on information and communications systems. The architecture and technologies that support this communication system are the key challenges to be addressed.

An important difference between the approaches of the US and the EU is the general perception of the air traffic control of UAVs in relation to the existing system of ATM of manned aircraft. In the US, a separate system is implemented for aircraft at altitudes below 400 ft AGL and in areas where no air traffic services are provided by the FAA but is complementary to the existing airspace management system in which the FAA provides services to aircraft flights. By contrast, in its final deployment, U-space in the EU will allow complex UAS operations to be performed in the same environment and ATM system.

Moreover, in UTM, the FAA delegates some of its airspace management authorities to other entities to provide management and services related to UASs. In the EU, an emerging concept is to integrate and accept UAVs into existing airspace management systems in a safe and proportionate manner, thereby creating a single entity with common management and control. Airspace management will be under the control of the CAAs as it is for manned aviation. Table 1 presents a comparison between the US and EU initiatives and the ICAO UTM framework: core principles for global harmonization.

Open issues and challenges

Of particular interest in the common framework with the ICAO Global Harmonization Fundamental Principles is the chapter describing the "gaps" and "challenges." The ICAO envisages significant growth in UAS operations, leading to a shift in focus toward low-altitude flights and overpopulated areas with various types of unmanned aircraft missions, such as flights and missions at altitudes below 150 m or 500 ft AGL. A greater number of operations are also envisaged, which raises questions about the viability and scalability of a UTM system and the ability of the ATM infrastructure to accommodate these new users. Reliance on communication links (either nontraditional, terrestrial, C2, or data communications associated with UTM systems) has also been recognized, raising new challenges regarding the frequency spectrum, resilience, and cybersecurity.

At the boundary between UTM and ATM systems and/or during the transition of drones between these systems, issues related to airspace classification, access to airspace, airspace rules, operational procedures, certification, data standards, position reports, and the interface between UTM and ATM are of particular importance. Aircraft participating in the UTM system must be separated from each other and from other hazards such as buildings, ground protrusions, or adverse weather conditions. The management of this separation should include direction and accountability, complemented by tools and strategies to address

Table 1
Comparative overview of EU and US regulatory initiatives.

Entity	ICAO	EASA and EUROCONTROL (EU)	FAA and NASA (USA)
Name	UTM	U-space	UTM
General perception	To support the organization, coordination, and management of unmanned aircraft operations in real or near real time, including the ability to control multiple operations beyond the visual line of sight.	In its final deployment, U-space will allow complex UAS operations to be performed with a high degree of automation in all types of operational environments, including urban areas.	A "traffic management" ecosystem for uncontrolled operations that is separate from the FAA's air traffic management (ATM) system.
Height	Below 150 m or 500 ft above the ground level.	Throughout the airspace.	Below 400 ft above the ground level. Planned for airspace where air traffic services are not provided by the FAA.
The aim is …	… the safe, cost-effective, and efficient management of UAV operations through the provision of systems and operations and a seamless set of services in cooperation with all parties and involving flying and ground operations.	… the uninterrupted conduct of air operations in all categories of airspace together with manned aircraft.	… the definition of services, roles and responsibilities, information architecture, data exchange protocols, software functions, infrastructure, and performance requirements for managing UAVs at a low altitude.
Relationship with the existing airspace management system		Integration and acceptance of UAVs into the existing airspace management system in a safe and proportionate manner.	In the existing airspace management system, the FAA provides services to aircraft flights to maintain airspace access and safety. In the UTM, the FAA delegates some of this authority to other entities to provide similar services.
Basic Principles	It should not adversely affect the safety or efficiency of the existing ATM system.	Maintaining flight and ground safety.	Collective management and safe operation of large-scale UAS operations in low-altitude airspace.
	Oversight of service provision, UTM, and ATM is the responsibility of the regulator.	Scalability and flexibility.	Satisfying service requirements and leveraging commercial activities.
	Maintain existing policies for the prioritization of aircraft (e.g., emergency situations).	Automation under control.	A secure and stable environment for operators to operate and satisfy business needs.
	Access to airspace should remain fair.	Equality and justice.	Operational framework consisting of standards, regulations, and common protocols.
	Certification of the necessary competencies of the operator and the remote operator of the UAS.	Competitiveness and efficiency.	Flexible and scalable structure that can adapt and evolve as the business space changes and matures.
	Access to UAS data by the competent authorities.	Use of the existing infrastructure.	A structure that allows the FAA to retain its authority but also allows other entities to manage operations in areas authorized for UAS.
	Creating, adopting, and maintaining a culture of safety.	Adoption of new technologies.	
	Free and open accident and incident reporting.	Risk and performance assessment.	
Contact	A distributed network of highly automated systems via application programming interfaces rather than voice communication between pilots and air traffic controllers.	An information-centric system where highly automated aircraft can fly safely based on the information that is exchanged and by using mobile networks.	A modern, computer-centric, federated approach that enables distributed airspace management where different entities work together to maintain a safe and accessible environment.
Services		U1 — Fundamental Services (e-registration, e-identification, and geo-sealing)	It comprises a set of federated services that are separate but complementary to air traffic control services and are based primarily on the exchange of information between air carriers on flight intentions and airspace restrictions.
		U2 — Initial Services (flight planning, flight approval, tracking, dynamic airspace information, etc.)	Supporting the safety and security of UTM operations including services such as flight planning, communications, separation, and meteorological data.
		U3 — Advanced Services (airspace capacity management and collision detection assistance, etc.)	
		U4 — Full Services (full operational capability of U-space)	

scalability.

Autonomy in a commercial aircraft is usually used to perform specific procedures that are highly complex and require very fast reactions, such as the flight control of an aircraft by design instability. Furthermore, in a traditional aircraft, the pilot is a critical component of the flight, as the pilot must have the ability to control the aircraft following very specific and understandable instructions and procedures. Nevertheless, modern technologies supported by advanced deep learning techniques (e.g., CNNs) can help AI to enhance robust autonomous systems and, thus, provide sustainable solutions in complex environments (Joint Authorities for Rulemaking of Unmanned Systems, 2023).

All air traffic services supporting ATM, which in turn ensures safety and optimal air traffic flow and separation must be explicitly determined and properly communicated to all airspace stakeholders using a highly efficient and automated communication and information system (CIS). Cyber threats can pose significant risks to CISs and the autonomous flights supported by those CISs. The increased use of automated/autonomous systems that rely on CISs also creates an increased need to protect the confidentiality, integrity, and availability of information. Thus, new systems must be designed to be robust and resilient to cyber threats. Cybersecurity must be integrated into the design of all new automated/autonomous systems, devices, aircraft, and airspace-supporting systems.

As mentioned earlier, the existing ATM system is human-centric and people are responsible for performing certain actions and reactions under certain circumstances according to well-defined policies and regulations. Depending on the technology used, some of these actions and reactions can be performed by automated/autonomous systems, but the responsibility still lies with humans. Although automation/autonomy covers most areas of ATM, it is important to define the role and level of human responsibility to ensure safe operations. The transition from human-centric to machine-centric architecture requires carefully designed systems to support efficient human intervention and decision-making, especially for handling unexpected or emergency situations as well as ensuring flight and ground safety.

Owing to the high level of automation, the architecture of a particular system is complex and cannot be described by system-level definitions that are useful only for high-level discussions and not for structured analysis and safety assessment. Automated/autonomous systems are expected to comprise several subsystems or activities, each of which may operate at different levels of automation; therefore, it is impossible to determine the level of automation of the system. A possible approach to address this issue could be a framework with different layers that can then be applied to higher levels of functional abstraction, such as collections of functions and subsystems of systems.

To transfer human tasks to automated/autonomous systems, people must strongly believe that automation will perform tasks as designed and deliver consistent results without unexpected behavior. To create trust, automated/autonomous systems must be developed based on robust design processes that fully implement safety assurance procedures commensurate with the safety criticality of the tasks planned to be dropped. The operating logic of automated and autonomous systems must follow a strict code of conduct that provides a high level of flight and ground safety assurance.

Conclusions

The safe and efficient operation of UASs in airspace management systems poses several challenges and involves many aspects, such as regulations, security and flight safety standards, collision risk prediction and avoidance technologies, and safety risk assessment. Various levels of ongoing activities and recent advances in UAS regulatory frameworks affect air transport in both the western and eastern parts of the world. Almost all aforementioned frameworks and concept initiatives are supported by research projects that examine and demonstrate their effectiveness and technological challenges. In this review, the most developed regulatory frameworks and concepts of international aviation regulatory authorities and major Eastern countries, such as the Russian UTM, Chinese UOMS, and Japanese JUTM, were examined and compared. Initiatives by Western countries, including the UK's Open-access UTM, the US's UTM, and the EU's U-space, have also been reviewed and compared, focusing on EU research activities and projects related to CONOPS.

Furthermore, relevant research conducted by the EU and other organizations such as academic institutions, consortia, and researchers worldwide was presented, demonstrating the challenges and technological solutions to address them. By reviewing and comparing the frameworks and concepts, it was found that the similarities between all initiatives were the common fundamentals of security, flight safety, and interoperability; the new M2M communication model; and the progressive approach to integrate the UAS into the existing ATM. In terms of differences, the novel findings and contributions of this review are the different approaches regarding the roles and responsibilities of state authorities in UTM management as well as the approach of integrating UTM into the existing ATM. Based on this research, scientific groups of regulatory authorities could consider the comparison of the frameworks and concepts detailed in this review to address the differences and develop a harmonized global UTM framework.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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No data was used for the research described in the article.

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