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Advances in low-altitude airspace management for uncrewed aircraft and advanced air mobility

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Autonomous systems

A B S T R A C T

Contemporary trends in Uncrewed Aircraft Systems Traffic Management (UTM) and Advanced Air Mobility (AAM) are redefining low-altitude airspace operations, particularly in urban and suburban settings where traditional airspace management approaches are inadequate to support the predicted air transport demands. To address these challenges, the development of an integrated Low-Altitude Airspace Management (LAAM) framework is seen as an essential next step, requiring new flight systems and infrastructure tailored to the distinct challenges of these environments. Cyber technologies, including automation and Artificial Intelligence (AI), play a crucial role in LAAM by integrating data from Communication, Navigation, and Surveillance (CNS) systems to support real-time and automated decision-making for separation assurance and flow management. While human operators and social interactions retain a very important role in LAAM collaborative decision-making processes, the reliance on automation is expected to continue growing, driven by the need to effectively manage the challenges arising from the increasing number and diversity of highly automated and uncrewed aircraft. Regulatory frameworks must adapt to accommodate the unique characteristics of AAM operations, ensuring the adequacy of safety standards and airspace regulations. In particular, airspace design is bound to evolve to accommodate Vertical/Short Take-off and Landing (V/STOL) aircraft's distinct capabilities and requirements. The deployment of AI in safety-critical systems will require rigorous verification, validation, and certification processes to ensure reliability and trustworthiness. To address these complex and interrelated challenges, a harmonized LAAM Concept of Operations (CONOPS) is needed, which should encapsulate both UTM and emerging AAM requirements, while clearly specifying the role of human operators for various levels of automation. Additionally, new system functionalities should be developed to enhance human-machine teaming by focussing on CNS performance-based airspace modeling and dynamic airspace management. Based on these premises, an integrated approach to Multi-Domain Traffic Management (MDTM) is emerging, with promising future perspectives for the safe, efficient and sustainable operation of highly automated and autonomous flight systems in all present and likely future classes of airspace.

1. Introduction

For decades, Air Traffic Management (ATM) has played a crucial role in ensuring safe and efficient aviation operations. Novel ATM technologies have been progressively implemented, particularly for enhancing air traffic safety, efficiency, and capacity [1]. The air traffic control service fulfils two main purposes: avoiding collisions and facilitating an orderly and expedited air traffic flow. The current operational organization of ATM services is based on the classification of flight operations as en-route, Terminal Manoeuvring Area (TMA), airport operations, and on the network management [2]. Communication, Navigation, and Surveillance (CNS)/ATM and Avionics (CNS + A) technologies are the primary system components as they allow the effective monitoring of the airspace, coordination between flight crews and ATM operators and precise routing of aircraft. Until recently, the responsibilities of the human operators involved in ATM – primarily Air Traffic Controllers (ATCo) – have been largely tactical and procedural in nature [3]. Conventional airspace, illustrated in Fig. 1, is comprehensively classified

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into two major categories: controlled and uncontrolled. ATCos actively monitor and manage the controlled airspaces, i.e., Classes A to C. Classes F and G are conventionally classified as uncontrolled airspace where ATCo has limited obligations to any aircraft. In most jurisdictions, the remaining Classes D and E involve a combination of controlled and uncontrolled traffic. This conventional organization is being reconsidered at present due to the rapid growth of Uncrewed Aircraft Systems (UAS) use cases and commercial interest in the past few years. The emerging need to integrate UAS traffic into the existing airspace bears notable challenges regarding increased traffic density and complexity in Low-Altitude Airspace Management (LAAM) [4,5]. The low-altitude airspace accommodates all types of UAS within the altitude of 400 ft above ground level but also expands the altitude range to 1000 ft to support urban applications. With the merging of UAS traffic into controlled airspace, The National Aeronautics and Space Administration (NASA) initiated research on principles of airspace integration. Six principles have been developed: no additional Air Traffic Control (ATC) infrastructure, no additional workload on ATCo, no additional requirements on traditional airspace users, providing an appropriate level of safety, enabling scalability in low altitude operations, and lastly, allowing operational flexibility [6,7]. In 2012, the Federal Aviation Administration's (FAA) Modernization and Reform Act prompted research into the field of managing small UAS (sUAS), which is a UAS that weighs less than 55 lbs or 25 kg [8], as civilian demand for these systems had grown significantly [9,10]. This initiative was pertinent to urban operations [11–13] and set the foundations for successive research efforts in this field.

In 2016, the FAA released Part 107, an addition to Title 14 of the Code of Federal Regulations (14 CFR), allowing routine sUAS operations in the National Airspace System (NAS) [14]. To date, UAS operations have largely been segregated from conventional aircraft. In instances where operations spanned controlled airspace, separation from other aircraft was ensured procedurally through an approval-seeking process with aviation authorities and visually by the remote pilot in charge. Current regulations allow Visual Line of Sight (VLOS) operations within both segregated and unsegregated airspace (subject to a lengthy risk assessment process). However, large-scale VLOS and autonomous Beyond VLOS (BVLOS) operations are not allowed within low-altitude airspace. To prevent interference with conventional aircraft, sUAS operations are limited to the open space below 400 ft (122 m) above ground level. However, with the increases in civilian UAS use cases and operations, it is evident that a dedicated management framework is required as traffic volumes scale up. The UAS Traffic Management (UTM) concept proposed and spearheaded by NASA aims to provide such framework for safely and efficiently managing the demand and complexity of future operations [7].

1.1. Low-altitude airspace management

In both USA (NASA) and Europe (SESAR), UTM research programs aim to address both the already identified and the potential future challenges: increasing risks of collision or safety hazards (e.g. traffic over urban/populated areas), traffic complexity as well as logistic feasibility and economic viability of services [15,16]. The UTM framework, as proposed and demonstrated through various trials, intends to support and enhance UAS operations in both VLOS and BVLOS modes [17,18]. In terms of airspace capacity, a large body of literature is available pertaining to conventional aircraft and ATM [19–23]. As originally envisaged, the UTM project is structured into four distinct phases or Technical Capability Levels (TCL). The progression of the project is characterized by increasing scenario complexity and required autonomous capabilities [13,16]. Each new TCL extends the capabilities of the previous TCL, with each sequential phase supporting a large range of UAS from remotely piloted vehicles to fully autonomous UAS. Each capability is targeted to specific types of applications, geographical areas, and use cases that represent certain risk levels. TCL4 is characterized by complex operations in densely populated urban areas and Urban Air Mobility (UAM). The benefits of UAS and mixed crewed/uncrewed operations under LAAM within these dense built-up areas, are being captured by the NASA Advanced Air Mobility (AAM) working groups, which have already identified numerous public and commercial use-cases [24]. This thesis addresses the requirements of both UTM and AAM under the LAAM framework.

In terms of capacity, the estimation of UTM airspace capitalizes on the ATM body of knowledge in this area, but its specificities are still an ongoing area of investigation [19–23]. Traditional ATM mostly caters to the need for Instrument Flight Rule (IFR) traffic, which is normally scheduled and planned in advanced, while UTM is facing less

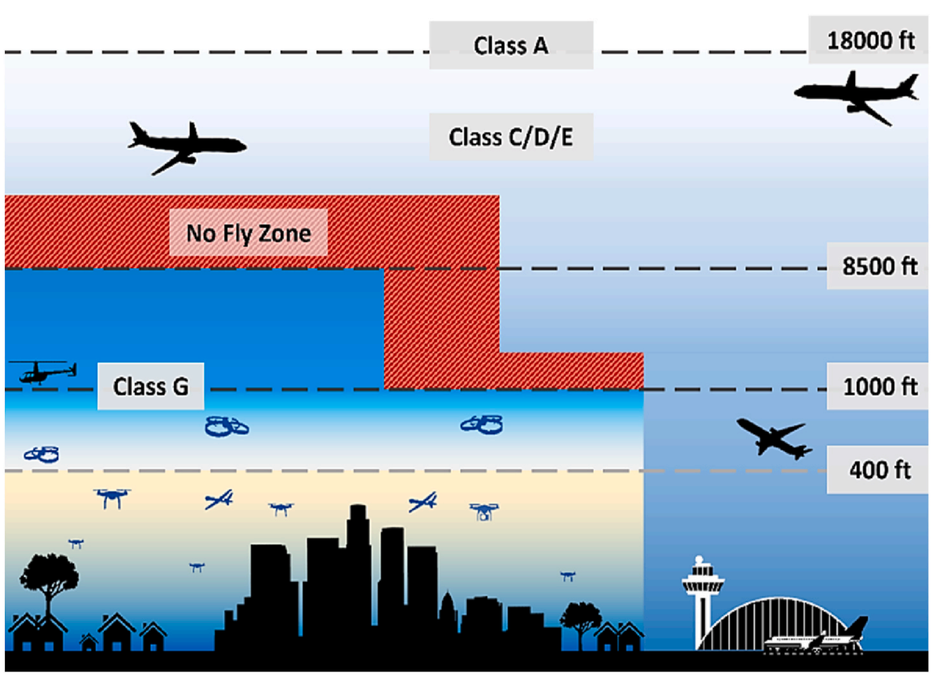

Fig. 1. Conventional airspace structure.

predictable traffic as in UAM or on-demand air taxi [25]. The ATM solutions as-it-is cannot be applied to UTM due to their different requirements, especially in high-density UAS traffic in urban areas. Hence, the UTM services must be flexible and structured only where necessary [26]. A higher degree of automation is expected to be exploited in UTM framework. This then imposes system constraints that are more computationally intractable. This cooperation will minimise the need for manual tactical deconfliction [27]. Therefore, the level of human engagement and the degree of automation need to be considered [28]. Even though UTM may go toward high autonomy, such a system still requires human accountability and responsibility for safe and efficient airspace as Eurocontrol states that "any future UTM system should be centered around the needs of its human operators by providing an automated setting that enables a human-in-the-loop system supporting the user as much as possible" [29].

1.2. Human factors in traditional ATM and LAAM

The safety and efficiency of air traffic management depend on the reliability and performance of both human operators and avionics systems. Rapid advances in avionics systems' technology have reduced the operator physical workload and are now progressively shifting mental workload from relatively low-level to higher-level tasks. Furthermore, human tasks have progressed towards passive roles such as monitoring, which frequently results in a loss of situation awareness [30]. For decades, Human Factors (HF) studies has been tackling such issues [31]. HF engineering, in particular, plays a crucial role in commercial aviation safety since it reduces the likelihood of human errors by enhancing the cognitive ergonomics and optimizing the system's Level of Automation (LoA). However, high automation in complex situations may result in inappropriate responses, requiring immediate human intervention. Therefore, the system needs parallel advancements with human engagement [32]. Historically, the SHELL model, invented in 1984, has been used as a HF tool to analyse multiple system component interactions [33]. The SHELL model assesses how human performance may be affected by its multiple and interrelated components: software (S), hardware (H), environment (E), and liveware (L). Another L is also represented by liveware, which is the heart of the model: at the center of the SHELL model lies the human operators of the considered process. In this paradigm, human errors can be seen as caused by a mismatch between liveware and the other four components. This model has been used in pilot cockpit improvement for better safety, efficiency, and human-machine interactions [34]. For ATM applications, the process was adopted to assess increases in LoA, particularly on computer-automation/information [35].

The design of future ATM systems requires adequate HF studies as an input, ensuring effective and useable design and operation [36,37]. While ATM procedures and interface technology are currently evolving to accommodate dense traffic, ATCo must retain a role in the process in all cases for several reasons: ATCo have achieved a high degree of safety and reliability in traffic management, humans have a great ability for problem-solving and optimization in complex situations, and even though automation has replaced some functions, ATCo are required to monitor at all times in case of unexpected situations [38]. The International Civil Aviation Organization (ICAO) has outlined various ATCo HF-related concerns with highly automated systems [39].

- Loss of situation awareness;
- Poor interface design;
- Automation intimidation;
- Boredom and automation complacency;
- Cognitive overload;
- Systematic decision errors;
- Over-reliance;
- Distrust;
- Confusion and misapplication mode.

Based on all these considerations and capitalizing on the considerable body of knowledge in Human-Machine Interfaces and Interactions (HMI^2), contemporary research in aerospace human-machine systems aims to combine and compensate for the strengths and weaknesses of both humans and present-day avionics/ATM systems. Automation shall be designed to work and assist cooperatively with a human operator to meet their mission requirements and responsibilities [39]. With the proliferation of highly automated and autonomous systems, the main target is to improve system performance, but a large body of such literature has not considered human cognitive limitations in parallel. This increases the probability for human operators to make mistakes when their cognitive capability is overloaded. One of the most promising approaches in this perspective is the Cognitive HMI^2 (CHMI^2) framework, initially developed by the Aerospace and Intelligent and Autonomous Systems research group at RMIT University [40–46]. This framework aims to promote collaboration and coordination between human and machine. Moreover, this development not only allows the operator to maintain better awareness of the autonomous system's actions but also prevents cognitive overloads and hazardous instances such as attention tunnelling.

Considering the differences in human operator roles in ATM and LAAM (highlighted in Fig. 2), the human operator in LAAM is expected to deal with a higher LoA than in ATM. The human operator's responsibility in LAAM to ensure safety and efficiency can no longer be fulfilled with the conventional, heavily tactical human ATC paradigm. In this transformation, it is envisaged that the objectives of ATM and its human operators will still be to prevent aircraft collisions with other aircraft and obstructions and to maintain an orderly flow of traffic. However, the responsibility-sharing between the human operator and the highly automated and autonomous ground/airborne systems will shift significantly towards the latter, which means that human roles are shifted from manual procedures to collaborative, highly automated decision-makers. These increases in automation complexity and the amount of handled information are eliciting a need for further research in HMI^2 for better human-machine teaming to improve the total system performance [47]. In recent years, progressively higher levels of automation have been introduced in Decision Support Systems (DSS) for ATM and Air Traffic Flow Management (ATFM) strategic and tactical operations [47,48]. Driven by a significant increase in air traffic complexity, automation levels are expected to increase even further in the emerging LAAM operational paradigms [6,7]. The aim is to support high-level human decision-making in the presence of dense, diversified and more complex traffic [25]. Thus, the human operator (LAAM operator) responsibilities are expected to shift away from tactical ("In-the-loop") duties to supervisory ("On-the-loop") control by increasing the role of airborne systems in tactical duties (such as separation assurance and collision avoidance) and by resorting to flow management measures (such as demand/capacity balancing) in all ground-based offline and online operational processes [49,50].

Important research and development efforts focus on monitoring and supporting the appropriate cognitive workload of human operators in complex and time-critical tasks through real-time measurement of neurophysiological variables [45,51]. Furthermore, because of the large

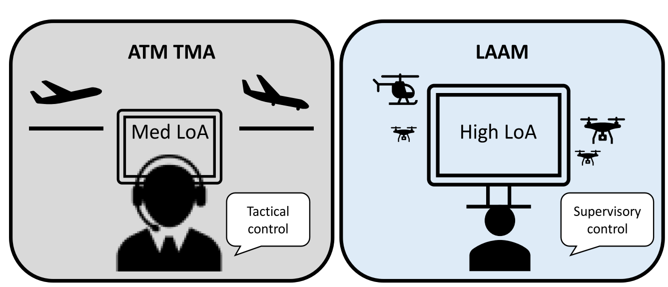

Fig. 2. Differences in human operator roles in ATM and LAAM.

amount of both historical and real-time data that has to be processed, the LAAM DSS necessarily makes use of various types of Artificial Intelligent (AI) algorithms, including machine learning, evolutionary algorithms and multi-agent simulations for evaluating and suggesting the best answer/choice to the human.

1.3. Key challenges posed by emerging operational concepts

Key features that need to be accounted in the UTM system are highlighted and summarised by the Global UTM Association (GUTMA) [52].

- **Digital**: reducing human workload, enhancing situational awareness and improving UTM services integration through real-time data exchange and high LoA decision-making procedure;
- **Flexible and modular**: having adaptable and flexible architecture to enable and incorporate new stakeholders and functionalities;
- **Scalable**: moving towards distributed responsibilities and services over the obsolete scheme, allowing to support high varied and dynamic traffic;
- **Safe and secure**: monitoring and maintaining safe and secure operations and conformance of mandatory operating requirements;
- **Automated**: needing highly automated DSS to assist human operators in ensuring safe and efficient operations;
- **Open-source**: offering a global approach towards creating and evolving the necessary services and protocols for scalable operations. Moreover, open-source components can speed up the development and deployment of UTM services.

The key areas that need to be addressed within the scope of this research are identified from the features mentioned above. Three aspects are discussed in further details in this section: 1) human responsibilities in highly automated systems mapped to digital, automated, and safe and secure features; 2) airspace modelling supporting diverse CNS performance mapped to digital, flexible, safe and secure, and automated, 3) traffic clustering mapped to digital, flexible, and scalable. The only feature not covered in this research is the open-source aspect since this research scope is within the development of key functionalities, not the full system development.

The development of LAAM has presented several challenges that must be addressed to ensure safe and efficient UAS operations. While traditional ATM is designed to cater to the needs of scheduled and planned IFR traffic, LAAM faces less predictable traffic patterns due to the nature of UAM on-demand air taxis and other UTM missions, which can start and end anywhere and have undefined levels of traffic [14–16,25,53–55]. This poses a critical gap in the current literature regarding the lack of a scalable deconfliction approach for LAAM [7,19–23,25,56,57]. A completely novel LAAM Concept of Operations (CONOPS) is being developed to enable the safe and efficient coexistence of UAS with conventional air traffic. However, CNS performance is crucial for LAAM airspace due to the challenges posed by the proximity to the ground [26,53]. However, the current LAAM CONOPS do not sufficiently consider CNS performance in key airspace functionalities such as Separation Assurance and Collision Avoidance (SACA) [26–28,58–61]. The LAAM system is a first-of-a-kind system that is not fully developed, and although it is assumed to be similar to an ATC system that operates parallel to conventional ATM but serves different altitudes and classes of aircraft, there are still open research gaps regarding the task demands and responsibilities of low-altitude management [62], which presents challenges for developing human-centric systems for LAAM. In any case, the role of traditional human ATM operators would not be able to cope with the envisaged density and complexity of UAS traffic; hence, the future LAAM operator will have to rely heavily on automation. Future research must address this significant gap in the key challenges faced by LAAM operators dealing with high levels of automation, which can frequently lead to mental overload and a lack of situational awareness [28,63]. Therefore, there is a need for human cognitive state monitoring/enhancement by machines to prevent cognitive overload and human oversight when increasing the level of autonomy in the system [40–46]. However, well-defined correlations between cognitive states and human neurophysiological responses are still the subject of ongoing research. Additionally, the reliability of the CHMI^2 sensor suite is important in sensing and inferring cognitive states. The performance characterizations of neurophysiological sensors, particularly cardiorespiratory sensors, have only been studied in physical activities [64–74].

The increasing volume of data and complexity of automation highlight the need for further research in the field of human-autonomy decision-making to develop safe and efficient LAAM services [75]. One of the key challenges in adopting traffic flow management methodologies in LAAM HMI^2 development is the computational complexity of the problem. Traditional traffic flow management algorithms accommodate an extensive timeframe to determine a solution. However, the predicted density and complexity of UAS traffic exacerbate the computing time requirements, making conventional ATFM timeframes no longer feasible since LAAM operations have a time horizon in the order of minutes [76]. Clustering allows us to deal with groups of entities instead of individuals, simplifying the problem space and lowering computational complexity. However, the most viable clustering method for LAAM is still undetermined. In addition, to convey the explanation to humans in a human-comprehendible form, the DSS also needs an associated HMI^2 explanation. Experienced human operators tend to be reluctant to adopt suggested solutions from the system if they are not trustworthy, tractable, and interpretable [77].

1.4. Structure of the article

Beyond the current section, which provided an evolutionary outlook of LAAM challenges, Section 2 discusses some fundamental concepts such as AAM operations, vehicles and route classifications. Section 3 covers the various proposed LAAM Concept of Operations. Section 4 addresses human and machine responsibilities. Airspace risk assessment processes are discussed in Section 5, while traffic complexity in LAAM is explored in Section 6. Section 7 focuses on AI algorithms in LAAM operations. Future developments are discussed in Section 8. A promising approach to Multi-Domain Traffic Management (MDTM), which harmonizes and integrates the most advanced LAAM operational concepts with emerging ATM and space traffic management paradigms is discussed in Section 9. Lastly, Section 10 provides some concluding remarks.

2. General vehicle and operational classifications

Within low-altitude airspaces, aerial vehicles present a mix of UAS and passenger air vehicle assets; hence, vehicle classification is essential to categorize different aircraft types for traffic management purposes. However, the classification of UAS and UAM is still evolving.

2.1. UAS classifications

The importance of classification lies in identifying and distinguishing vehicles with their unique flight dynamics and performance characteristics of power plants. A natural approach is a weight-based classification such as Maximum Take-Off Weight (MTOW)-based [55] and air-weight-based [78]. MTOW-based classification ranges from micro UAS, which weigh up to 200 g, to large UAS, which can weigh up to 47,580 kg. In addition, the US Defense Advanced Research Projects Agency (DARPA) has introduced an even lighter class than the micro UAS called Nano UAV for civil leisure applications [79]. The weight of these vehicles ranges between 3 and 50 g with less than 1 km flight range. Similarly, even smaller UAS used for leisure activities were defined as Pico UAV, with weights from 0.5 g to 3 g and a comparable size to insects or coins [80]. However, although the weight categorization reflects the system's complexity and its performance to some degree, it does not precisely capture the differences in the vehicle operational characteristics, which are the significant factors that make UAS traffic operations more complex than traditional crewed aircraft operations.

Based on RTCA DO-320 [81], conventional aircraft performance is adopted to categorize UAS operational performance, including airship, turboprop fixed-wing, turbojet fixed-wing, Vertical Take-Off and Landing (VTOL), and electric fixed-wing. For micro air vehicles, the FAA developed a performance-based standard dedicated to this particular vehicle operating over people [82]. On the other hand, the US Department of Defense adopts UAS weight, airspeed and operating altitude to identify UAS classes [83]. In the UK, an MTOW-based classification was adopted as the primary method [84]. Later, in 2015, the Remotely Piloted Aircraft System (RPAS) categorization was published, and the classification changed from MTOW-based to risk-based [85]. A risk-based approach was also adopted by EASA, categorizing RPAS operations as Open (low risk), Specific (medium risk), and Certified (high risk) [86]. A vehicle classification is not adopted by EUROCONTROL, but traffic classification is used, with traffic divided based on flying rules and operational procedures [54]. In China, the Civil Aviation Administration of China (CAAC) adopts multiple factors as their UAS categorization: weight, application type, configuration, and operational requirements [87].

As mentioned earlier, a proposed MTOW-based classification provides a reasonable basis for classifying aircraft based on the risk posed to humans and properties. Altitude-based UAS classes are also of interest since collision avoidance requirements can be specified [55]. Another proposed classification is area-based, which considers the location of flight operations: rural areas, populated areas, urban areas, and open-air assembly of people. Nominal or off-nominal trajectories can be involved in these operational areas; with the same weather conditions, each area will have its environmental conditions for LAAM operations, such as atmospheric boundary layer conditions and manmade structures [78]. Additional information on flight areas is based on the mission objective [11,78], which aids in raising awareness of situations for human operators. The generic mission is divided into three types: surveillance, support, and entertainment [11]. Other classifications are speed categorization, operational controls, flight rules, and engine types. The flight rule categorization includes VLOS, BVLOS, and First-Person View (FPV) BVLOS. The operational control categorization consists of direct control, mode control, flight plan control, and autonomous control. The four standard engine types are piston, turboprop, jet, and electric. An overview of existing UAS classifications is presented in Fig. 3.

2.2. Passenger transport aircraft classifications

Passenger transport aircraft are a larger transport category, which includes both crewed and uncrewed aircraft. The vehicle classification based on engine types consists of spanning multi-rotor, tilt-wing, tilt-rotor, and powered wing [88,89]. The types of take-off and landing capabilities are VTOL and Short Take-Off and Landing (STOL) [90]. Fig. 4 illustrates different types of passenger transport aircraft. Advancements for these aircraft are progressively made in electric/hybrid propulsion systems, automation levels and digitalization, lightweight materials, and energy storage. Similar to UAS, the automation levels and performances significantly vary across vehicles and operational missions.

2.3. Airspace categories

Airspace structure is an open research gap for low-altitude airspace operations. The primary factors that are vitally important for the airspace structure layout for low-level traffic management are route types and operational areas. These two factors are captured in mission-based classification. As briefly mentioned in the previous paragraph, four types of operation areas are identified as [78].

- **Rural Area** - open airspace, minimum risk probability;
- **Populated Area** - open airspace with moderate obstructions of manmade structures, medium risk probability;
- **Urban Area** - near the boundary of or below the urban canopy with dense obstructions of manmade structures, high-risk probability;
- **Open-air assembly of people** – over-people assembly in an open area, high-risk probability.

2.4. Route and mission classifications

Operational areas are expected to have unique airspace structures,

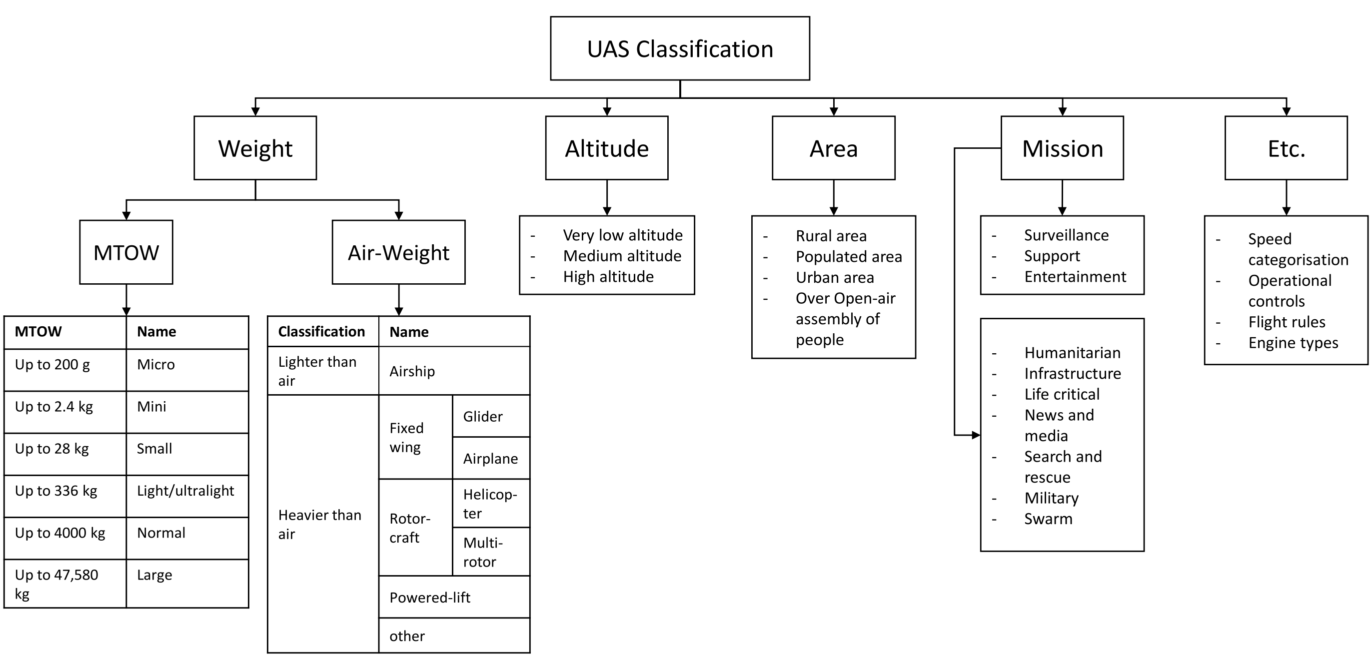

Fig. 3. Summary of UAS classifications [11,55,78].

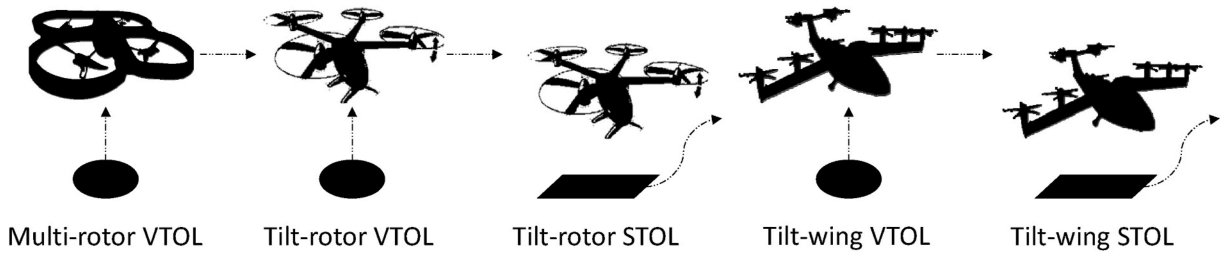

Fig. 4. Passenger transport aircraft types in low-altitude airspaces. Adapted from Ref. [90].

which are affected by different flight operations and environmental conditions. Furthermore, to ensure safe operations and to keep traffic ordered, the following routing strategies have been defined for different UAS applications and possibly different layers of airspace.

- **Free route** - free routing is when aircraft can fly any path, so long as their planned path is coordinated with and deconflicted from the paths of other aircraft by a LAAM operator and approved based on calculated risk.
- **Fixed route** - fixed flight routes (corridors) are defined to ensure safety when a high-density air traffic stream is present or in any location where such structure is required to ensure safe operations. This could include locations such as airports or warehouses.

These routes are then subdivided into four route types [91].

- **Out-and-Back (radius mission)** - routes start and end at the same location and follow a single route or multiple routes to an end point and then return along the same route;
- **Point-to-Point (range mission)** - routes begin and end in different locations;
- **Loop** - routes start and end in the same place but follow a non-repeating route around the area;
- **Loitering** - routes start and end at the same location as Out-and-Back but loiter around one position before going back to base.

Passenger transport aircraft are largely operated within two operational categories [90].

- **UAM** – urban area, point-to-point short to medium range mission;
- **Regional air mobility** – rural area, point-to-point short to medium-range mission.

To summarise the operational classifications in low-level airspace, Table 1 maps missions and their subcategory with their route type.

Table 1
High-level summary of potential low-level traffic operations with route type.

Operation	Category	Sub-category	Route type
Surveillance	Single-user data collection	Personal UAS for site surveillance	- Free route - Loitering
	Multi-user data collection	- Search and rescue mission - News and media report - Traffic monitoring - Weather - Patrol monitoring	- Free route - Point-to-Point - Loitering
	Emergency support	- Natural disaster - Accidents - Fire - Homeland security - Infrastructure inspection	- Loitering - Loop - Out-and-back
Support	Communication Airborne refuel/recharge Emergency	- Data relay - Military, customs, or police services - Life critical medical delivery - Firefighting operations	- Loitering - Out-and-back - Fixed route - Loop - Out-and-back
	Payload drop	- Courier service - Sensor tag - Micro-vehicle deployment - Humanitarian mission	- Fixed route - Point-to-Point - out-and-back
Entertainment	Tourism	- Visual tours	- Loop - Scenic route
	Individual application	- Recreation - Movie shooting	Free route
Formation or swarming flight			- Free route - Point-to-point
Transport			- Fixed route - Point-to-point

2.5. VTOL certification

The certification of VTOL aircraft marks a significant advancement in the development and deployment of AAM services. Recognizing the unique requirements of these emerging technologies, EASA introduced its SC-VTOL-01 framework on July 2, 2019 [92], aimed at regulating VTOL aircraft. Following this, in November 2022, FAA proposed specific airworthiness criteria for the Joby Aero, Inc. Model JAS4-1 powered-lift aircraft [93]. Acknowledging the critical need for harmonization in regulatory standards, EASA requested an extension of the public-comment period until December 22, 2022, to align FAA and EASA criteria for powered-lift aircraft. By June 2024, significant progress towards this goal was evident as the FAA issued draft certification criteria for powered-lift aircraft under Advisory Circular 21.17–4 "Type Certification—Powered-lift" [94], while EASA concurrently updated its SC-VTOL framework to SC-VTOL-02 [95] to further align with FAA standards. This collaborative effort underscores the essential role of international cooperation in advancing unified certification frameworks, which are crucial for ensuring global operational standards and safety in the rapidly evolving field of aviation technologies. Table 2 summarizes EASA and FAA certification framework.

3. Concepts of operations

Low altitude airspace operations accommodate various types of traffic, as described in the previous section. Considering that the nature of such traffic is significantly different from traditional ATM traffic, this poses several challenges for the system development [96]: lower operational altitudes, higher operational densities, greater diversity of operations, and varying vehicles' and operators' performance. As a consequence of these challenges, the conventional ATC system capabilities and airspace are not scalable to directly apply in LAAM [97]; therefore, a new system is needed to accommodate this emerging operation. Prominent organizations have been developing their LAAM CONOPS, with some organizations focussing on UTM CONOPS while others focus on UAM/AAM CONOPS developments. This section reviews the LAAM CONOPS proposed by various countries and highlights the main contributions of key stakeholders in this domain: NASA and U-Space. The section further extends the scope of the literature review to identify the key priorities to be addressed in this area.

3.1. LAAM CONOPS

The CONOPS developed around the globe provide an overall proposed system architecture and general guidelines for UAS and crewed vehicles operating in low-altitude airspace. It is important to note that the CONOPS are not yet finalised as it has been continually matured to date. A common goal for LAAM operations is to achieve innovative solutions through partnerships with public and private organizations. To enable safe integration of UAS with other airspace users, the document outlines rules and regulations that shall be implemented. Some common rules and regulations are [98].

- Flyzone outside aerodrome traffic zone;
- Flyzone 5 km from airports;
- Flight altitude150m (500 ft) from crowded area;
- Flight altitude 50m (170 ft) from people and property.

The LAAM CONOPS has been developed to consider the most likely use cases for low-altitude airspace operations. The LAAM environment is intended to facilitate business activity associated with UAS/crewed vehicle use while providing adequate safety and public acceptance. Even though the use cases consist of a mix of vehicle types, the LAAM operations, including all UAS missions, do not directly interact with the conventional ATM system. To ensure effective and fair access to low-altitude airspace for all aircraft operators, the FAA, SESAR, and other responsible authorities worldwide, such as the FAA and SESAR, have focused on developing qualitative and quantitative components based on users' perspectives.

The main details of the CONOPS are continually developed in the US and Europe. Currently, the UTM CONOPS from NASA and FAA are not based on an open-sourced architecture, which according to GUTMA poses a challenge to being accepted globally in the short term, as already discussed in section 1.3. The core of the UTM system is the Flight Information Management System (FIMS), which interacts with UTM Service Suppliers (USS) under FAA constraints. In contrast, U-space from Europe features a web-based portal that architects can easily access through an accessible gateway, which helps them continuously improve and evolve U-space in the future [99]. The U-space also further develops and investigates the adoption of ATFM in UTM operations – notably with a Demand-Capacity Balancing (DCB) process for UTM operations detailed in the SESAR DCB document [50]. Looking at other countries, the first country to initiate and implement UAS legislation was Australia, which established Civil Aviation Safety Regulation (CASR) Section 101 in 2002 [100]. The UAS legislation categorizes by the UAS's weights and their application purposes, which are commercial or recreational. The approval is not required, given that certain safety guidelines are followed for recreational purposes [101]. For UAS weighing more than 2 kg, the operator must obtain a Remote Pilot's License from Civil Aviation Safety Authority (CASA) to fly commercially. Compared to the UK, UAS of less than 20 kg are regulated for recreational purposes based on their aviation regulations: Articles 94, 95 and 241 of the Air Navigation Order (ANO) 2016 [102]. A Civil Aviation Authority (CAA) permit is required for UAS operating below the minimum altitude from the public and buildings [103]. In Singapore, Civil Aviation Authority Singapore (CAAS), together with Nanyang Technological University (NTU), have developed a plan and regulations specifically for densely populated airspace in an urban environment. Their research focuses on implementing fully connected VLOS and BVLOS UAS flying below 60 m (200 ft) in the urban area based on a Long-Term Evolution (LTE) cellular connection [104–106]. In South Korea, the Ministry of Land, Infrastructure, and Transport (MOLIT) has established the K-drone system mainly for safe and secure flights, i.e., collision prevention and UAS flight monitoring. The system was developed by the Korea Institute of Aviation Safety Technology (KIAST). For UAM, the MOLIT is developing 3D low-altitude airspace systems for the air-taxi mission and expects to announce the air-taxi city roadmap in 2025 [107]. In 2015, the CAAC collaborated with EASA to develop a unified system called UAS Operation Management System (UOMS), which is a system specifically for UTM services [78,108]. The UOMS is one of the first frameworks that cover the scope of UAS interacting with ATM when necessary [109]. The development of the UTM prototype in Japan stands out in terms of the government sector (Japan Meteorological Association) and private stakeholders' collaboration, such as Hitachi, NEC Corp, Rakuten, NTT DATA and Docomo, etc. Such collaboration has demonstrated safe and secure high-density UAS operation (146 flights per hour within 1 km^2) in at the Fukushima robot test field. They have one of the world's largest UAS test field facilities, where they have tested three main functions: collision avoidance, forced landing and falling, and real-time tracking for airspace and flight status [110]. Moreover, the Japan Aerospace Exploration Agency (JAXA) has developed a simulated environment for the UAS delivery mission setting in 2030 called the "scalable simulator for knowledge of low-altitude environment" (SKALE). The delivery operation enables the BVLOS flights over high-populated areas, which aligns with [111]. Fig. 5 illustrates the overall delivery operation where the cruise altitude is 120 m. The study has shown that conflict detection and resolution need to be extensively improved to accommodate dense and highly automated vehicles. Separation distance and flight speed also require further study and modelling [112].

The previous paragraph has summarised the proposed CONOPS globally. The following subsections will further detail the CONOPS from the two main contributions for LAAM operations, NASA/FAA and U-space.

Table 2
EASA and FAA VTOL certification framework.

Aspect	EASA	FAA
Certification Framework	Special Condition for VTOL (SC-VTOL-01), updated as SC-VTOL-02 in June 2024	Proposed Advisory Circular 21.17–4 "Type Certification—Powered-lift"
Weight Limits	Maximum certified take-off mass: 12,500 lb (5700 kg)	Maximum certified take-off mass: 12,500 lb (5700 kg)
Performance Categories	Basic and Enhanced categories	Category B (essential performance) and Category A (increased performance)
Survivability Provisions	Provisions for survivability in water landings	Safety requirements for a buoyant, water-tight passenger cabin for water landings
Redundancy Requirements	Requirements for redundancy in systems	Specific requirements are not detailed, but the safety continuum based on risk exposure
Maintenance and Training	New rules for electrical wiring maintenance and technical training	General safety and maintenance requirements for powered-lift aircraft
Safety Levels	Higher safety levels based on the number of passengers and public risk exposure	Four certification levels based on passenger capacity and public risk exposure
Regulatory Harmonization	Ongoing efforts to align with FAA standards, updated in SC-VTOL-02	Draft policy statement "Safety Continuum for Powered-Lift" to harmonize with EASA standards

3.1.1. NASA/FAA CONOPS

A considerable emphasis of published UTM CONOPS is placed on operations in any airspace lying in the first 400 feet above ground and, consequently, these documents address uncontrolled (class G) and controlled (classes B to E "surface") airspace operations that are becoming increasingly complex. A series of scenarios are presented, which include operations within controlled airspace that occur in BVLOS conditions [7,13,113]. The UAM corridors and aerodromes that have been proposed to support UAM operations are shown in Fig. 6. These corridors accommodate UAM aircraft, helicopters, and fixed-wing aircraft (and possibly UTM vehicles). The description of the operations within the UAM corridors is as follows [114].

- Rules, procedures, and performance standards specific to UAM apply to all aircraft;
- UTM-coordinated vehicles and fixed-wing aircraft operate only across UAM corridors;
- UAM aircraft and helicopters operate within or across UAM corridors;
- Class of airspace does not affect operations.

The CONOPS provides a framework for UTM/UAM ecosystem development and identifies operational and technical criteria. A comprehensive definition of UTM/UAM services is provided in detail from fundamental functional aspects, allowing the various stakeholders to create strategies to implement LAAM.

The UTM architecture proposed by NASA/FAA (Fig. 7) emphasizes two main aspects: FAA and other industries' development and deployment. Airspace restriction data is provided to operators by the FAA, which regulates and operates flights. In this case, the operators are the Pilot in Control (PIC). To facilitate effective information-sharing, the FAA communicates with UTM when necessary and accesses information via the FIMS, which acts as a core component of the entire UTM ecosystem, delivering all UTM members the essential traffic management framework. On the other hand, the industry development and deployment's responsibility are to maintain services and components in the UAS infrastructure. The essential information distributed among UTM stakeholders is performed through a coordination channel (USS) [113].

A UAS operator or airspace user is responsible for the overall operation of the system, including aircraft flight planning, intent information sharing, and ensuring safe operations. The safety of UAS flights falls within the pilot's responsibilities, such as obstacle detection and avoidance, following flight restrictions and airspace constraints, and flight tracking (local). In addition, to help operators safely and effectively use airspace, USS offers services that meet the operational requirements of UTM, e.g., critical information sharing, flight planning, and global tracking.

The nominal architecture for UAM is very similar to the one for UTM [114] (Fig. 8). The additional component here is the Provider of Services for UAM (PSU), which acts as a center of the UAM architecture. PSUs exchange data with all stakeholders, such as USS, FAA, PIC/UAM operators, and Supplemental Data Service Providers (SDSP). UAM operational data is received by PSU from SDSP, and relevant information is distributed to the public. UAM and UTM operational information is exchanged between USSs and PSU. Based on its services, a USS can expand into a PSU and vice versa. Both the UTM and UAM environments will be supported by combining service providers. The UAM CONOPS v.2.0 emphasizes cooperative operating practices between stakeholders, airspace structure (corridor), and the importance of performance-based construct and DCB services [115].

Looking into the research and development initiatives led by NASA as part of its TCL roadmap, UTM technology will be implemented and tested closely with various industry partners. The TCL roadmap consists of four phases: TCL-1 to TCL-4. With each phase, the complexity increases, and the technical objectives are specific. As the research progresses, specific technical goals are set to demonstrate the architecture, services provided, and support needs of the final system. TCL are structured based on three factors: safety, density, and level of technologies. Safety refers to risk-oriented operation criteria, including ground and air population density. The various TCL are tailored for different LoA. Fig. 9 illustrates how TCL capabilities increase in functionality, type of application, geographical location, and use case based on specific risks.

TCL-1 implies a lower level of complexity and lower operational risk. VLOS operations under low traffic density and remote populations were addressed, including rural applications such as bushfire, infrastructure, and agriculture monitoring. The airspace usage and re-adjustment of flight plan are managed and reported by the UAS operators.

TCL-2 refers to BVLOS operations over sparse populations, which were conducted at the Nevada test site in October 2016 [116]. As a result of the TCL-2 test, a long-range operation can be achieved with moderate-low traffic levels in rural/industrial areas. The applications of multiple BVLOS operations in TCL-2 are contingency management, tracking and operational procedures.

TCL-3 involves a crewed and uncrewed BVLOS safety operation, such as the delivery of packages, which was tested in 2018 [17]. Cooperative and non-cooperative UAS monitoring was conducted over suburban applications with moderate traffic density. The proposed next-generation Traffic Alert and Collision Avoidance System (TCAS II), so-called Airborne Collision Avoidance System X uncrewed variant (ACAS Xu), has assessed its capabilities with human-in-the-loop experiments [117,118].

TCL-4 builds on TCL-3 to offer more advanced capabilities in dense urban areas. BVLOS operation and constraint are expanded at this level to accommodate flight information and large-scale contingency management of the whole UTM architecture comprising collision avoidance and geofencing. Since TCL-4 adopts a high level of automation, advanced applications are also involved: autonomous Vehicle-to-Vehicle (V2V) communication and autonomous UAS operation. In August 2019, the test was conducted over high-traffic density locations in Texas and Nevada testing sites [119–121]. According to further studies by NASA, dedicated simulations are required for small UTM systems evaluation in low altitudes, which prompted the development of the Fe-cubed (Fe3) simulator to evaluate the specific performance of UAS, which has been utilized to lower operational risks and traffic bottlenecks [122–124].

Similarly, the development of UAM is divided into six phases based heavily on the degree of automation called UAM Maturity Level (UML) [114]. The initial phase entails UML-1 and 2. The UML-1 focused on flight testing in limited environments where UTM dominates technology and framework. The UML-2 tested assistive automation for low-complexity and density commercial operations. This phase also envisioned self-managed operations of UAM corridors in controlled

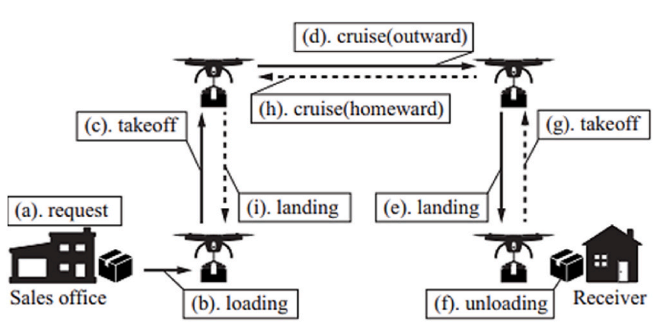

Fig. 5. Passenger transport aircraft types in low-altitude airspaces. Adapted from Ref. [90].

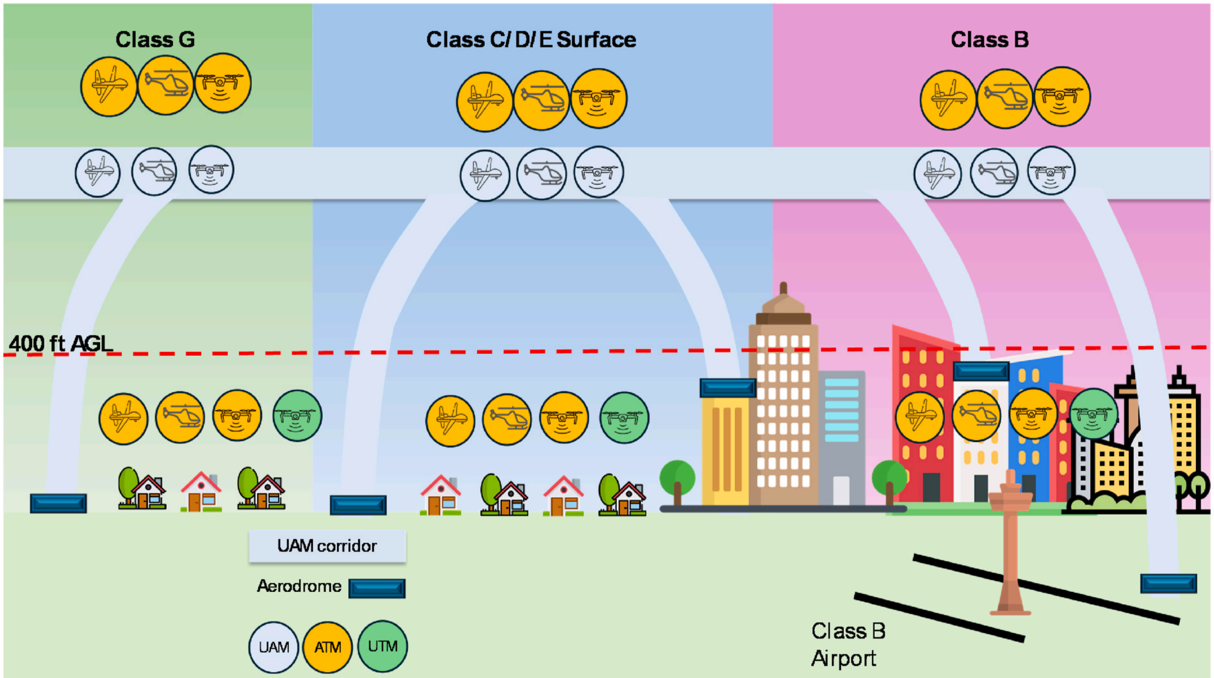

Fig. 6. ATM, UTM, and UAM operating environments [1].

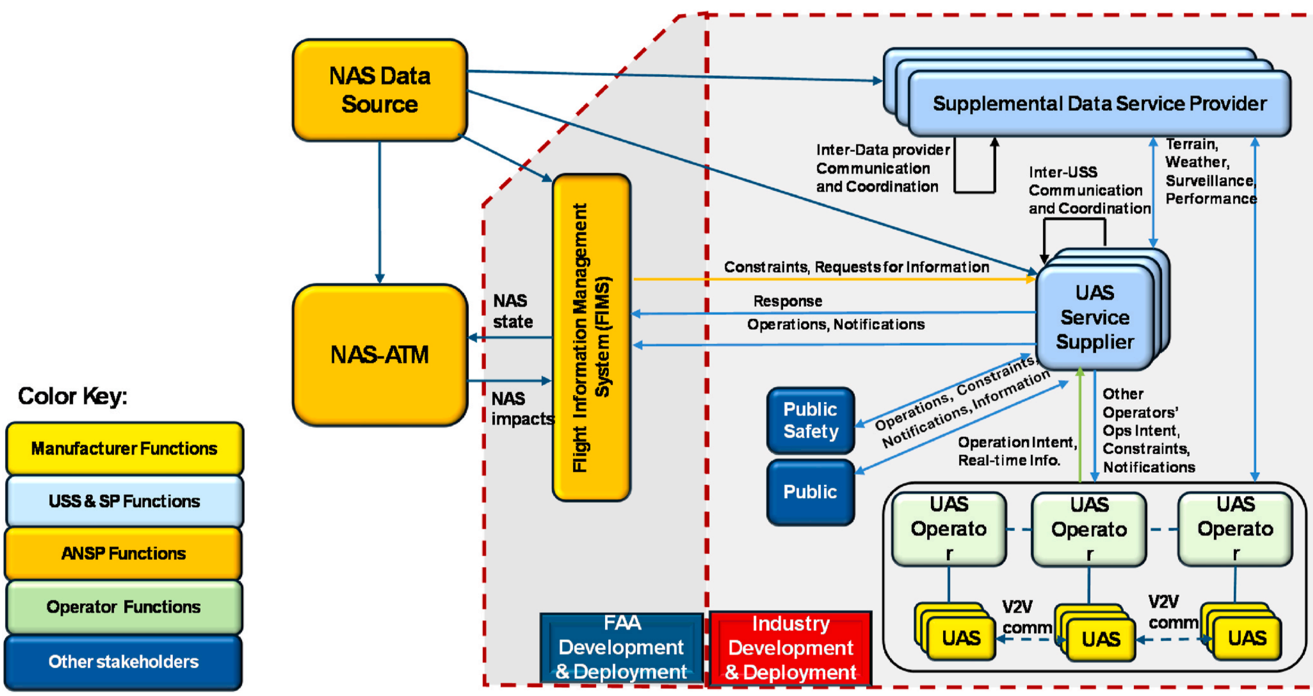

Fig. 7. FAA's notional UTM architecture [113].

airspace. UML-3 and 4 are part of the intermediate stage where UML3 reflects low-density and medium-complexity traffic while medium-density and complexity traffic is reflected in UML-4. The automation for safety assurance, validation of operational airspace, CNS considerations for UAM vehicles are addressed in UML-3. The collaborative and responsible automated system is addressed in UML-4, along with the study of high-capacity UAM ports and low-visibility operations. The operational altitude of 1000 ft is aimed for UML4-6 operations by integrating LAAM into the National Airspace System (NAS). The mature state consists of UML-5 and 6, which can be mapped to UTM TCL-4, meaning that they will operate in high-density and complex traffic over urban areas. The main difference between levels 5 and 6 is the level of automation and its applications: UML-5 only focuses on highly-integrated automated networks, while UML-6 focuses on system-wide automated optimization [125]. The overall evolution of the low-altitude airspace is summarised in Fig. 9, highlighting the differences in risks, levels of automation, and operation types for vehicles, airspace, and system aspects. The vertiport supporting full-scale UTM and UAM operations is *High-Density Vertiplex*, a vertiport automation system for high-throughput operation in UML 4–6 [126]. NASA has also

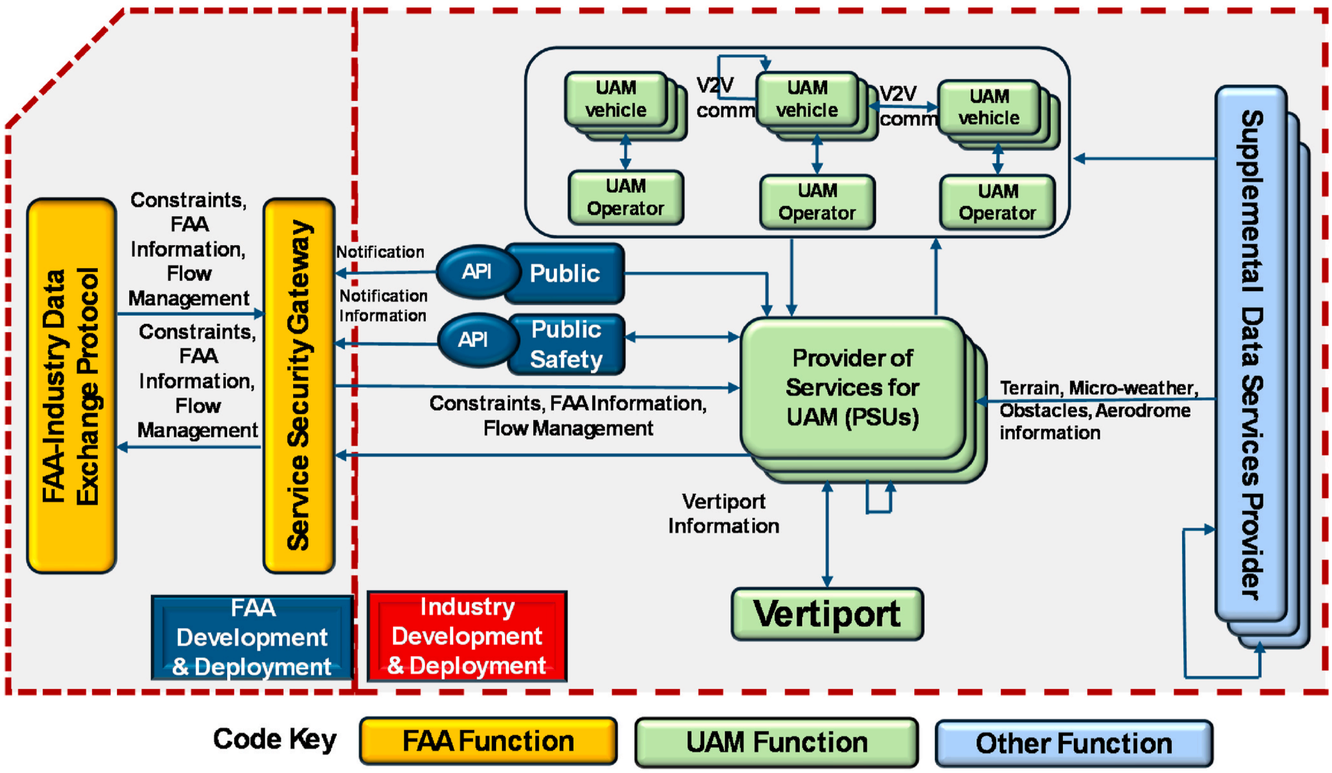

Fig. 8. FAA's notional UAM architecture [114,115].

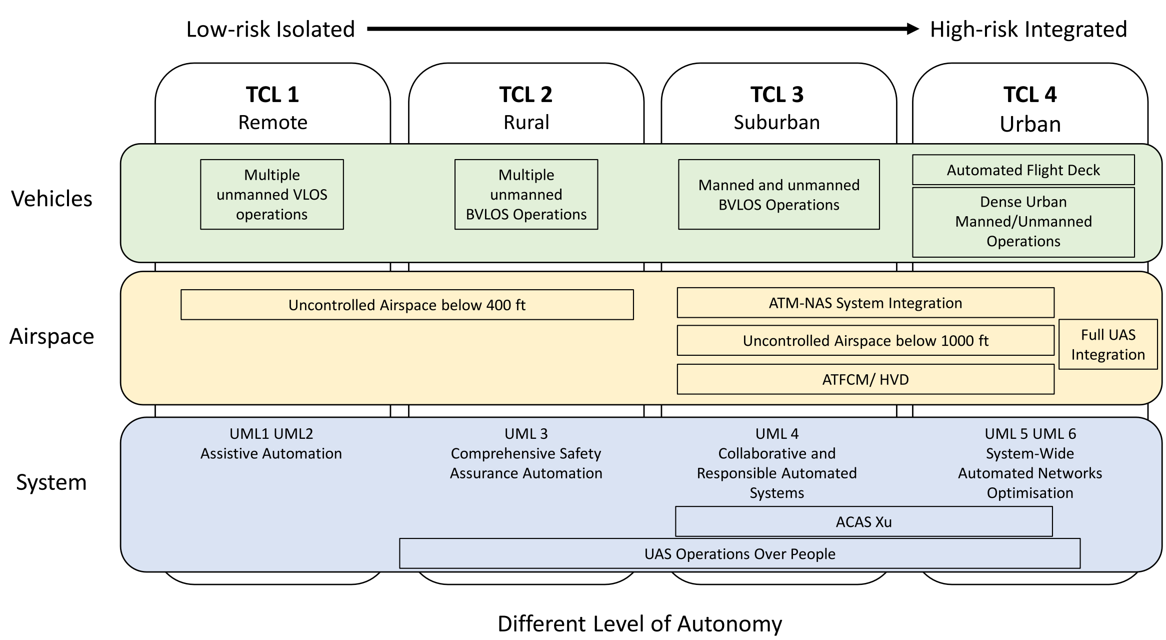

Fig. 9. NASA's low-altitude airspace management evolution (TCL roadmap).

applied Air Traffic Flow Capacity Management in strategic conflict management for UAM operations, specifically in managing DCB at vertiports [127].

Fig. 9 also outlines different levels of autonomy throughout each technical phrase; however, both UTM and UAM CONOPS fail to specify the adopted LoA in the system. The UTM CONOPS depicts only a "highly automated system" will be implemented [7]. Only the aircraft LoA are identified in UAM CONOPS, which describes the engagement between the UAM vehicle system and PIC. The evolution of aircraft automation is divided into the following categories [114].

- **Human-in-the-Loop (HITL):** the automation (systems) are always under the direct control of humans;
- **Human-on-the-Loop (HOTL):** human responsibility is a supervisory control where active monitoring of the systems is performed, and full/override control can be enacted whenever required;
- **Human-over-the-Loop (HOVTL):** the automation (systems) informs human of the actions taken. Human performs passive monitoring to

identify when and what action is required, especially when automation's actions are not reconcilable or as part of rule set escalation.

Initially, the UAM aircraft LoA is consistent with the technologies currently used on crewed helicopters. HOVTL capabilities could be achieved through automation improvements in UML 5–6.

Considering the constraints of emerging LAAM operations, the anticipated high density in urban areas and vertiports results in a separation of less than the three-mile standard separation rule; therefore, it is necessary to introduce new separation guidelines and alternative airspace rules. The management of BVLOS operations requires strategic conflict resolution, position, and intent, and exchanged data sharing with other nearby UAS. The operator also needs to monitor flight conformance, notify in-flight conflicts and re-routing, and monitor weather conditions and CNS systems. In accordance with UTM CONOPS, UAS must receive 4DT performance authorizations with a collaborative pre-deconfliction computed prior to the flight. For UAM vehicles, airborne avionics must be equipped with detection and avoidance systems and precision navigational capabilities. Evidently, the CNS infrastructure is another big challenge in LAAM operations since various existing technologies have technical disadvantages and need to be advanced to achieve the desired performance. In air navigation systems, while sensor fusion remains as a core technology, Global Navigation Satellite System (GNSS) with augmentation are the recommended primary means of positioning, e.g., GNSS with inertial navigation systems, GNSS with Satellite-Based Augmentation Systems (SBAS), Ground-Based Augmentation Systems (GBAS), Wide Area Augmentation System (WAAS), etc. The major challenge for communication systems is limited bandwidth, which elicits novel frequency management approaches using AI. However, the barrier to such adoption is the verification and FAA certification standards unless AI-enabled technologies are used in limited functions. The alternative technologies for LAAM communication systems are 5G cellular and satellite integration, advanced frequency management, Low Earth Orbit (LEO) communication, etc. Last but not least, the current ADS-B in and out is expected to be exploited. At the same time, alternative technologies are also investigated, such as ACAS X/Xu, K Band Radar, LiDAR, dedicated short-range communications, etc [128].

3.1.2. SESAR U-space CONOPS

Various stakeholders have contributed to the UTM CONOPS as part of dedicated NASA working groups. Similar efforts in Europe have also lead to the so-called U-space CONOPS. EASA has initiated and proposed a high-level ecosystem for the U-space, prompting the need for the U-space Service Providers (USSP) to properly support multiple actors simultaneously [129]. Many research institutes in collaboration with EUROCONTROL have developed the U-space CONOPS under the project of European Unmanned Traffic Management Systems (CORUS) which focusses on a very low-level airspace operations (500 ft and up to 1000 ft in some zones) [130]. All vehicle sizes and classifications detailed in Section 2 are covered within the scope of this CONOPS. The U-space operating environment differs from the NASA UTM CONOPS: airspace within a very low level is divided based on service types into three volumes (X, Y, Z) illustrated in Fig. 10. The X volume is the low-risk VLOS zone where no conflict resolution service is provided. The higher-risk VLOS and BVLOS zones are the Y and Z volumes, where pre-flight conflict resolution is offered based on permission constraints related to technical capabilities. The Za volume denotes the area where LAAM operations intersect with ATC controlled airspace, while Zu and Zz remain under U-space control. In Zu, the tactical conflict resolution service issues instructions that the UAS must follow, whereas in Zz, the tactical conflict resolution service provides advice only [131]. Table 3 summarizes the access conditions, the mandatory services, and possible operations in X, Y, and Z volumes.

As mentioned before, USSP is the key module of the U-space architecture, which is highlighted in Fig. 11. The system architecture was a modified version of the Unifly system to simplify and facilitate different activities and services within the U-space [132]. The human operator within the USSP is called the U-space Service Manager (USM), whose duties include the coordination of the following pre-flight and in-flight tasks.

- **Pre-flight services**: encompassing an initial flight plan, pre-tactical geofencing, and strategic deconfliction;
- **In-flight services**: including tactical and geo-awareness emergency management.

For emergency management services, relevant warning inputs are received from external stakeholders (e.g., firefighters' declaration of a wildfire). In addition to interconnecting all U-space service providers, the ecosystem manager acts as a governing body and a single source of truth. In cases where safety is compromised, the ecosystem manager imposes a solution to ensure equitable access to the airspace of all users. The manager provides several centralized services, such as airspace data provision, ATC coordination, and reliability, integrity, and completeness level of the needed information assurance. This role is envisioned to be performed by the Member state [132]. The remote pilot is responsible for UAS's flight status, where the responsibility varies based on the LoA. Similarly, the UAS operators that manage a fleet or group of vehicles are also responsible for associated flight statuses.

From the UAM perspective, even though the U-space CONOPS states that they cover all types of LAAM vehicles, the context is mainly limited to the UAS vehicle. SESAR has a specific project named Uspace4UAM, tackling very high LoA, digitalization, and connectivity for all airspace users in very low-level urban areas. The project aims to achieve UAM to deploy fully autonomous taxiway services [133]. Unlike the NASA CONOPS, the U-space CONOPS did not categorize the UAM level separately; hence, the U-space levels cover both UTM and UAM operations. The CORUS CONOPS define the U-space levels into four phases (U1, U2, U3, and U4) based on the gradual deployment of services and where technology is implemented as it matures. Fig. 12 summarizes and highlights the key elements of each level ranging from U1 low level of connectivity and LoA to U4 high level of connectivity and LoA.

U1 refers to the foundational services of U-space, which were defined in 2019 for class G airspace below 400 ft, to address multiple crewed and uncrewed operations with low traffic density. Restricted locations were supported, with geo-awareness and registration being the basic capabilities of U1.

U2 provides initial services for BVLOS operations in high-traffic density areas, including controlled airspace. It establishes a procedural interface with ATC. Additionally, it encompasses drone operation management, which includes flight planning, approval, tracking, and the provision of dynamic airspace information.

U3 offers advanced services for BVLOS operations in dense and complex airspace, such as suburban environments and UAM applications. It employs advanced and high LoA interfaces with ATC. The services at this level include geo-awareness features, such as dynamic geofencing, dynamic capacity management, and conflict detection. The U3 capability is anticipated to be operational by 2027 [134].

U4 envisions the full integration of UAS in dense urban areas, characterized by a very high LoA for both vehicles and network systems, as well as U-space infrastructure. The complete implementation of ATM and U-space services is expected by 2035 or beyond. The U-space services corresponding to U levels 1 to 3 are illustrated in Fig. 13.

The CONOPS also states the possibility of a fully automated flight in the future; however, in the meantime, a human supervisory involvement is still required. Moreover, automated decision-making systems are being investigated for real-time conflict resolution and threat management, but the LoA needs to be clearly defined [135]. Overall, the U-space

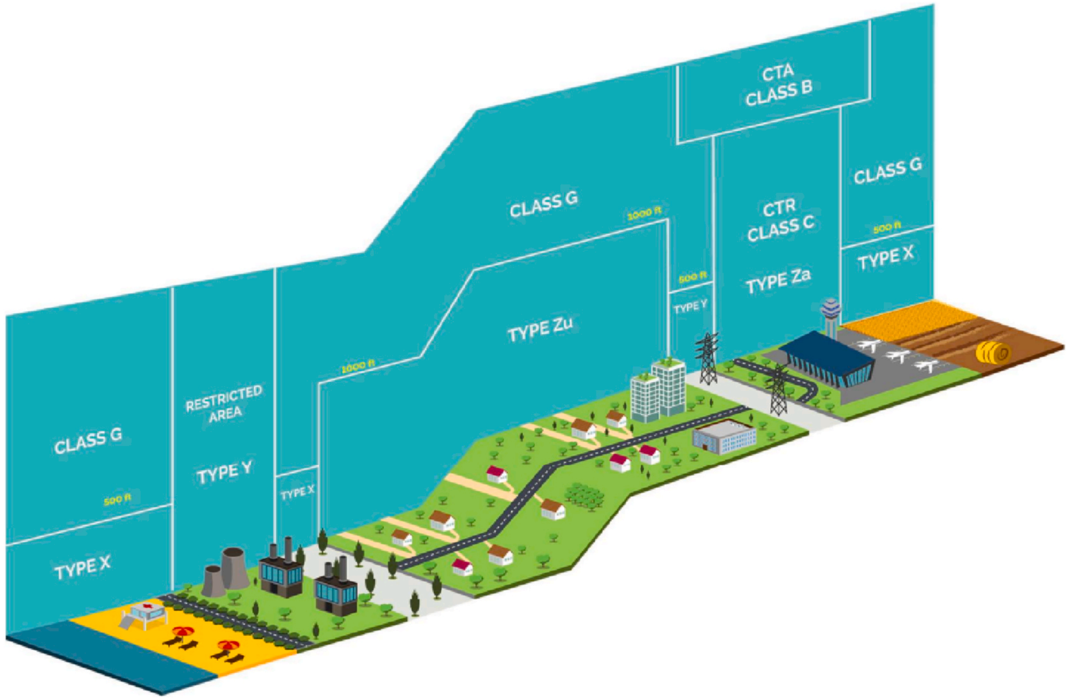

Fig. 10. Very low-level operating environments [130].

Table 3
X, Y, and Z volumes operations and services.

	X	Y	Z
Access conditions	Few basic requirements for the operator, the pilot, or the drone The pilot remains responsible for collision avoidance at all times	Requires: an approved operation plan, a pilot trained for Y operation, a remote piloting station connected to U-space, a drone and remote piloting station capable of position reporting when available	Requires: an approved operation plan, a pilot trained for Z operation and/or a compatible, connected automatic drone, a remote piloting station connected to U-space, a drone and remote piloting station capable of position reporting
Mandatory services	Registration Traffic Information Incident/Accident Reporting Vertical Conversion Emergency Management	In addition to X volume mandatory services: Tracking, Flight Authorization, U-plan processing, Geo-awareness (including dynamic Geofencing), Strategic Conflict Prediction and Resolution, Monitoring, including Conformance Monitoring, Collaborative Interface with ATC, Vertical Alert and Information, Navigation Infrastructure Monitoring, Digital logbook	In addition to Y volume mandatory services, requires: Dynamic Capacity Management, Tactical Conflict Prediction and Resolution, Procedural Interface with ATC.
Possible operations	Drones: VLOS Other flight modes require risk assessment Other airspace users: crewed VFR flight	Drones: VLOS, BVLOS Other flight modes require risk assessment Other airspace users: crewed VFR flight	Drones: VLOS, BVLOS, automated flight in Zu Other flight modes require risk assessment Other airspace users: crewed IFR and VFR flight

CONOPS emphasizes the adoption of very high LoA but is not specific, while important missing elements are CNS technology challenges [136]. CORUS also anticipated some challenges from adopting such high LoA, such as misinterpretation of automation mode or any flight deck information provided; hence, the design of HMI[2] is vital in the U-space system.

Furthermore, SESAR research and development has significantly contributed to developing the U-space DCB management in great detail, described in the following subsection.

3.1.3. U-space DCB concept and process

The Demand and Capacity optimization in U-Space (DACUS) project, as part of the SESAR joint undertaking, has developed the DCB for U-space CONOPS specifically for urban airspace operations [50]. The DCB concept and processes have been developed to be inherently service-oriented, take advantage of increased levels of automation, and allow a large variety of new business models to be implemented. These DCB services are expected to be mandated at the U3 level. Similar to the traditional ATFM, the DCB management aims to prevent exceedance of maximum density levels and airspace capacity overload. However, since the traffic in U-space is different from commercial operations in terms of high mission diversity, it varies in CNS and other vehicle capabilities; hence, as part of how to manage the DCB process in U-space, these factors need to be addressed.

DACUS has identified four main services offered in the DCB U-space, as illustrated in Fig. 14. Despite the fact that the tactical conflict resolution service is depicted in the figure, such service is not an integral part of the DCB process.

The following services are active participants to the DCB process.

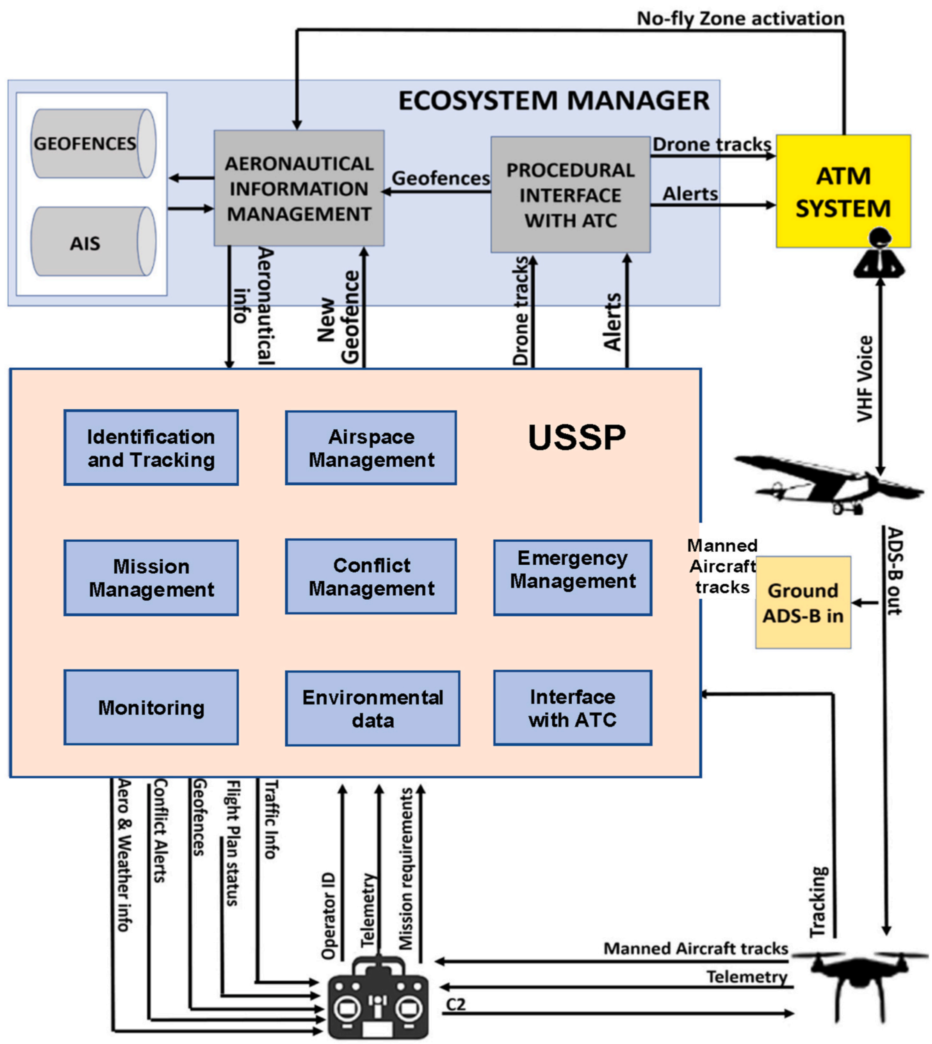

Fig. 11. U-space reference architecture [132].

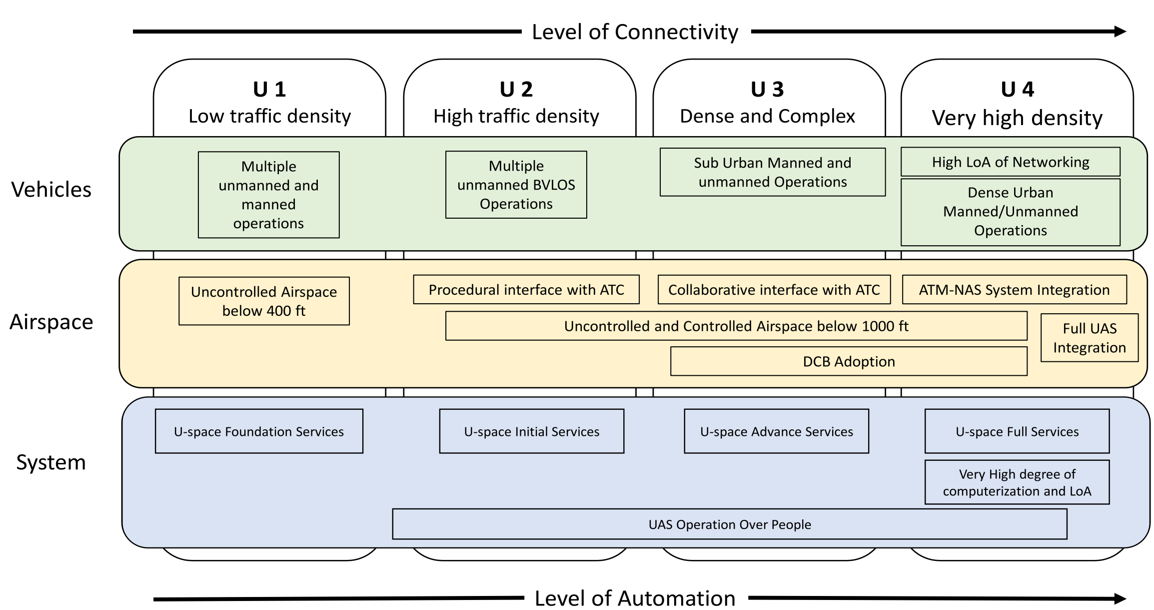

Fig. 12. U-space low-altitude airspace management implementation levels (evolutionary roadmap).

- The operation plan preparation includes the initial plan drafting and its submission. The submitted plans are verified for consistency and probabilistic 4D trajectories are generated.
- The submitted operation plans are compared with approved plans by the strategic conflict resolution service. If the conflict risk exceeds a set limit, solutions will be proposed considering the UAS mission objectives;
- The proposed solutions or DCB measures are assessed by the dynamic capacity management service based on safety and social impact indicators. The effects of such DCB measures on the missions and the indicators are also calculated and monitored.

Similar to the traditional ATM, the five phases are adopted in the U-space DCB process: long-term planning, strategic, pre-tactical, tactical, and post-operational phase. Table 4 details overall tasks in each phase with each process and involved U-space services.

DACUS has mentioned several challenges regarding LoA and CNS performance and capabilities diversity. Different types of disturbance may prove challenging in urban environments, especially with a high density of UAS. For instance, UAS emergencies may occur frequently possibly leading to the UAS operator being unable to safely manage in-flight contingencies with consequent need for higher LoA. Regarding the CNS performance challenges, if demand leads to the need for more capacity, that capacity may be obtained by restricting and requiring high CNS performance, which results in smaller separations. The technical limitations of providing DCB solutions in U-space are studied with an extensive literature review, highlighting the need for novel U-space DCB measures that were not implemented in ATFM.

3.2. Airspace modelling

Traditionally, airspace for commercial aircraft is defined by ICAO based on flight types, separation provision, air traffic service types, ATC clearances, altitude and speed limitation, and radio communication requirements. Hence, airspace is categorized into classes A, B, C, D, E, F, and G (uncontrolled airspace). The adoption of these classes varies across countries depending on their airspace characteristics [137]. This structure, which is handled by the controllers in each sector, currently manages almost all aircraft in controlled airspaces. The services and information, such as trajectory assignment and separation management, are transferred from one sector to another. With the nature of low-altitude airspace operation that is probable to operate in class G and the overlapped altitude in other classes, except class A, the airspace-based operations are not feasible for LAAM. To increase ATC capacity and improve the current system to manage such additional low-altitude traffic, the development process is expected to be expensive and take a very long time due to its non-scalability and the existing high throughputs [138]. A new airspace structure design that can accommodate high traffic complexity and increasing throughputs is needed to support low-altitude airspace operation [58]. However, the consensus on LAAM airspace design is still an open research gap [28,61,139]. This section presents the review of airspace structure design and capacity proposed in the literature. The review of traffic separation is summarised to understand the overall operational separation in LAAM.

Airspace sectorization is a key factor in managing air traffic complexity, human operator workload, and demand-capacity balance. However, owing to the difference in operational complexity, traffic volumes, fleet mixes, and supporting infrastructure, it is readily apparent that airspace design and sectorization strategies for conventional air traffic are inapplicable in their current form to the UAS/UAM traffic management problem. While various sectorization concepts and models have been proposed in the literature, as of today, none has been standardized or even agreed upon to cover the whole spectrum of LAAM operations.

As mentioned above, airspace structure design is an important aspect of UAM/UAS integration and to date remains an open research gap in the literature. Although lessons learned in conventional ATM are useful, many legacy solutions cannot be scaled down and directly applied to the local management of UAM and UAS [24]. Table 5 summarizes the main airspace structure concepts that have been proposed in the literature so far. Four concepts are readily discernible: full mix, layers, zones and tubes. These are described in detail in Refs. [28,61]. In the full mix concept, the airspace is essentially unstructured, with vehicles using a direct route between their origin and destination, with optimized flight

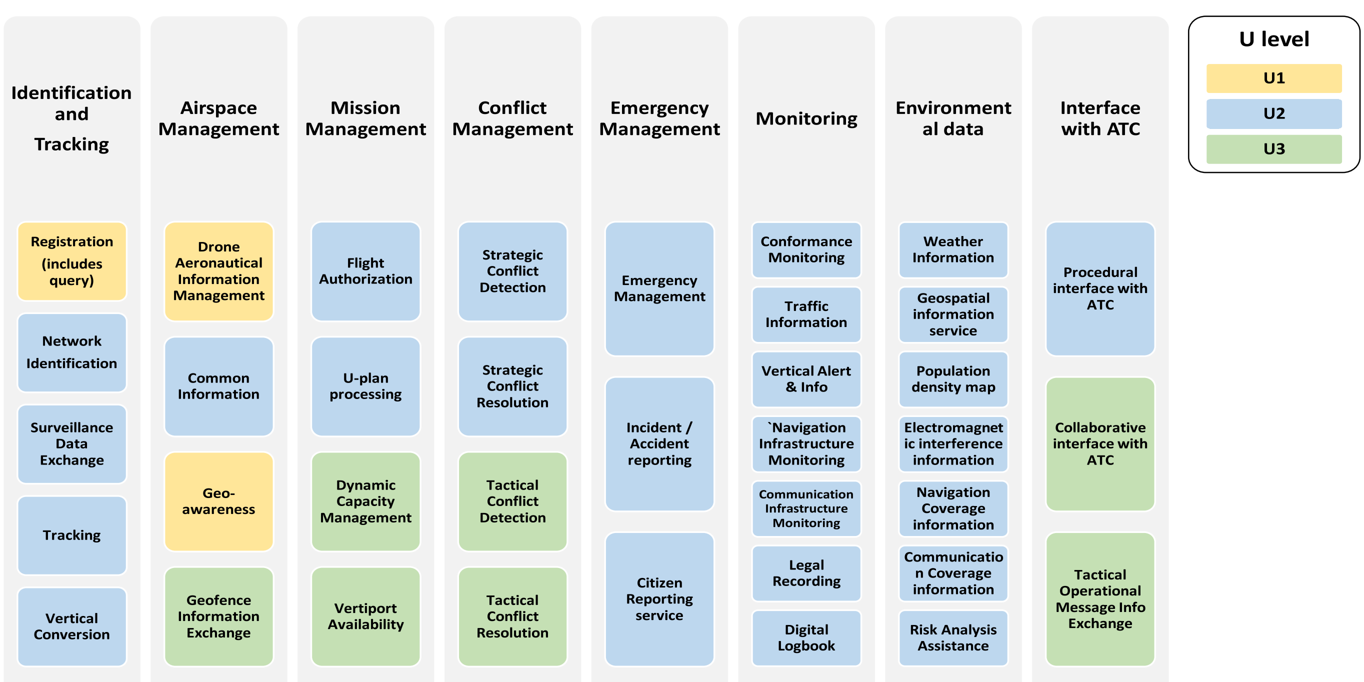

Fig. 13. U1, U2, and U3 services. Adapted from Ref. [131].

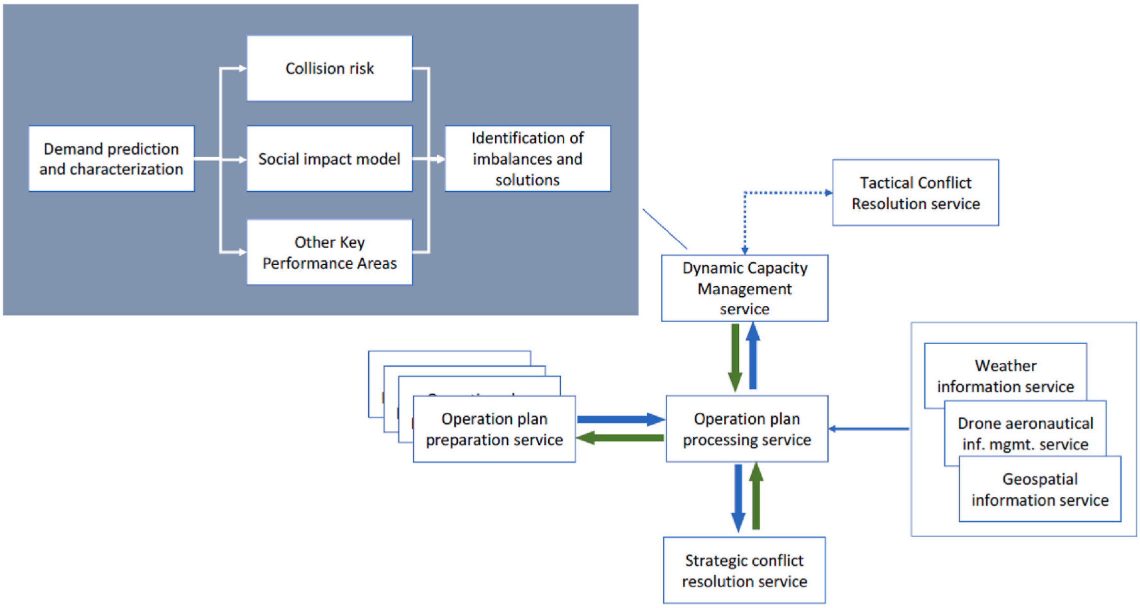

Fig. 14. DACUS DCB service interactions [50].

Table 4
Five U-space DCB phases with their services.

	Long-term planning	Strategic	Pre-tactical	Tactical	Post-operational
Timeline	Months/years*	Days/years*	Hours/minutes*	During the operation execution	After day of operations
Service 1 The operation plan preparation	Initial identifying major imbalances in capacity and demand	Submitting the operation plans	Penalizing the unexpected operation plans	1. Reporting different disturbance types triggering the initial plans (CNS/weather/etc.)	Assessment of the implemented DCB measures and the overall process efficiency and providing feedback by all stakeholders
Service 2 The operation plan processing		Validating the operation plans and generating probabilistic 4D trajectories	Recalculating all 4D trajectories		
Service 3 the strategic conflict resolution		Detecting potential conflicts and identifying solutions	N/A	2. Managing the disruption triggered by the disturbance	
Service 4 Dynamic Capacity Management		Calculating uncertainty and demand prediction	Recalculating uncertainty and demand prediction		
Service 5 Dynamic Capacity Management		Monitoring safety and social impact indicators	Monitoring safety and social impact indicators	3. Calculating and identifying DCB measures based on which types of disturbances they are facing	
Service 6 Dynamic Capacity Management		Assessment of pre-defined DCB measures. This strategic phase will focus on ensuring greater stability under changing demand	Assessment of pre-defined DCB measures on the high level of confidence ensuring the effective implementation of the DCB measures	4. Assessment of the proposed DCB measures and implement them	
Service 7 Dynamic Capacity Management		Identifying potential DCB measure towards the implementation options	Prioritising operational plans, proposing changes with the least virtue. Two approaches are envisioned		
Notes	Not managed by U-space DCB services	Execution of a DCB measure that does not impose a significant constraint on the mission	Implementation of the DCB measures that were not executed and consolidation of the global traffic	The tactical conflict resolution service is responsible for all processes in this phase	

altitudes and velocities to minimise fuel burn and other related costs. In the layered concept, the airspace is divided into sections stacked on top of each other. Each layer is typically dedicated to a type of aerial vehicle and a specific heading. The zone concept divides the airspace into different regions on the basis of a set of criteria. This typically includes risk exposure to people and property. Lastly, tube-based airspace structures are centered on fixed corridors; vehicles must follow a common speed limit, thus ensuring safe separation and minimizing conflicts. The so-called "stacked-layer" concept is also gaining traction, with one proposal to split each layer into so-called sky lanes in urban centers that mimic the organization of streets [58]. Each lane is a rectangular bar-shaped space extruded from a square that confines the height and width of flight trajectories, as shown in Fig. 15a. The separation assurance from other vehicles and static obstacles is maintained by onboard autonomous systems and/or remote pilots. The flow of traffic is essentially managed by offline or online design/redesign of the lanes. Situations in which lanes intersect are managed by a time-based prioritization for each lane, conceptually similar to how traffic lights are applied to road traffic. This traffic control service is provided via radio communication by UAS Traffic Flow Control system infrastructure built at the intersection and illustrated in Fig. 15b. Another layered airspace concept that is analogous to road traffic is presented in Refs. [27,60], where roundabouts are used at the junction of multiple sky lanes in place of time-based separations.

In [140], air corridors are generated by modelling UAS as particles in an ideal fluid flow field, using streamlines to safely navigate around buildings and obstacles, as illustrated in Fig. 16. This process involves discretising the airspace into coordination planes and solving the Laplace partial differential equation to determine the stream function, ψ, which guides the safe path of the UAS. Air corridors are defined by connecting nodes or cells with equivalent ψ values, while boundary and obstacle constraints ensure safe navigation around the airspace.

The zone concept has also been proposed in the literature as a means of dividing the airspace into operational volumes. In several proposals in the literature, the division is typically performed on the basis of the level of risk exposure to the general public. Alternatively, the division can also be performed on the basis of the services provided and on the level of overall system performance required to support a given category of operation. Access to a particular zone is then contingent on the UAS meeting the level of system performance stipulated for that zone. This mirrors the implementation of Performance-Based Navigation (PBN) for crewed aircraft, wherein the employed navigation systems are required

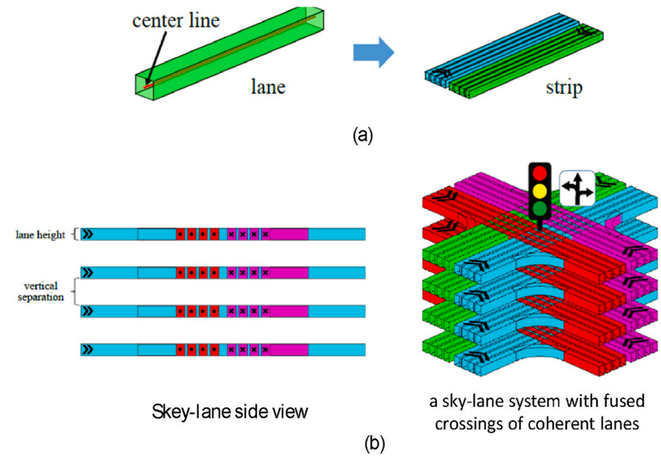

Fig. 15. Sky-lane structure concept.

to meet a certain level of performance depending on the region and phase of flight. In fact, PBN has been endorsed by NASA [141], as a potentially viable concept to adopt and apply to the airspace structuring problem in the UTM context. This is also emphasized in the NASA AAM initiative [142]. Navigation performance for UAS can vary to a greater extent than crewed aircraft.

Most UAS navigation systems employ a GNSS receiver as the primary source of positioning in a global frame. This is typically supplemented by fusion with other sensors, including inertial sensors, visual sensors, and LiDAR, to obtain a full navigation state estimate. The achievable performance is dependent on the individual sensor characteristics as well as the employed fusion algorithm. Performance is also dependent on environmental characteristics that are different from those encountered in crewed aircraft operations. For example, GNSS performance is highly degraded in urban environments owing to signal multipath and obscuration relative to conventional crewed aircraft operations. Therefore, greater reliance on augmentation with visual sensors and intelligent fusion algorithms is necessary.

An adequate adaptation of PBN to the UTM context would support this widely varying performance. Further, the PBN concept should be complemented by performance-based communication and surveillance (PBCS) standards. PBN and PBCS would together support the broader concept of Performance-Based Operations (PBO). However, there has been limited investigation into this aspect for LAAM. Amazon has proposed a similar approach to PBO, where a lesser-equipped vehicle can operate in a remote area.

On the other hand, highly prescriptive standards must be met when operating in an urban area [98]. Duchamp [26] presents a PBN-inspired approach using a graph algorithm to separate UAS traffic into different levels; congested city zones are divided into a larger number of layers and in contrast, low-density airspace is structured with a lower

Table 5
Summary of proposed airspace structure concepts.

Airspace Concept	Structure Type	Layout	Benefit
Jang D.S. et al. [58]	Layer	Lanes Traffic lights at intersections	Save space Avoid congestion at intersections Simple
Sacharny S. et al. [27]		Lanes Roundabouts at intersections	Simple Decrease traffic delays at intersections
Sedov L. et al. [60]		Lanes	Consider vertical separation loss
Duchamp V. et al. [26]		Lanes Corridors	Simple Flexible routes PBN-inspired density-based layers
ONERA [143]		Buffer zones	Risk-based layers Reduce collision risks
CAAC [144]		Vertical zone based on aircraft sizes	Simple Flexible routes Minimise risks
Sunil E. et al. [28,61]		Lanes Tubes and cones for landing	Balance safety and efficiency metrics
	Full mix	Free flights Landing/take-off strips	Very flexible flights
	Zone	Lanes Octagon arcs at intersections	First Come – First Serve (FCFS) principle Simple to implement
	Tube	Fix routes Layers	Increase traffic predictability
K.H. Low et al. [145]	Tube and Zone	Lanes	Simple Simplify complexity Minimise risks
Amazon [146]	Zone	Vertical zone Speed categorisations	Simple
JAXA [147]	Full mix	Free flights Corridors	Very flexible flights

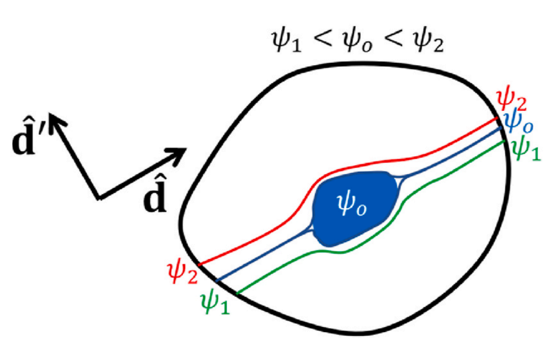

Fig. 16. Visualization of obstacles absorbing streamlines with their ψ value [140].

resolution. In Ref. [148], the airspace was partitioned into so-called 'airboxes' considering communication performance.

The airspace capacity is defined as the maximum number of aircraft in a sector that can safely accommodate, estimated from the controller's workload under constraints and airspace structure [20,21,149]. In addition, capacity metrics also support the assessment of human controller workload together with other metrics such as dynamic density and traffic geometric complexity. However, the exact definitions of these metrics are very specific [150]. Accordingly, the capacity estimation should be less dependent on the controller's workload with the foreseen high autonomy in LAAM operations. The airspace geometries, mix of traffic, ATC services and separation are the factors to determine airspace capacity and vice versa. Safety is a constraining factor that should always be considered in a multivariant optimization [139].

Currently, the users in low-altitude airspace (uncontrolled airspace class G) are almost uniquely general aviation. The upcoming VLOS and BVLOS UAS traffic are expected to populate the airspace region in greater multitude. The low-altitude airspace, therefore, should accommodate this traffic mix irrespective of their sizes and capabilities [16,28,114]. Furthermore, various additional factors have to be considered when the traffic is operating in the urban area: noise level, social impact, atmospheric boundary layers, etc. The lesson learned from distributed air/ground traffic management literature has guided some metrics to apply in capacity evaluation for free flight UTM operations: performance, safety, and stability [151,152].

Based on the Metropolis project, the layer-based airspace can be assumed to estimate capacity [150]. The study aims to investigate the relation between capacity and safety. The study's primary concern is the safety factor; hence, the adopted metric is the global conflict rate. The definition of *global conflict rate* is the number of possible combinations of two aircraft multiplied by the conflict rate for any given pair. The capacity estimation is then derived as:

$$N_{max} = \frac{1}{2}L + \frac{1}{2}\sqrt{L^2 + \frac{8LCR_{max}}{kf(\alpha)}} \tag{1}$$

with $f(\alpha) = \frac{1}{\alpha}\left(1 - \frac{2}{\alpha}sin\frac{\alpha}{2}\right)$

Where L is the number of layers, CR_{max} is maximum global conflict rate, k is a coefficient representing other influences, $f(\alpha)$ is a function of the reduced effect of relative velocity, α is a heading. This equation also considers relative velocity and spreading effects across each layer. A similar capacity evaluation concept is proposed with the addition of a traffic complexity study by using geovectoring [153].

Furthermore, graph theory or a random geometric graph [154] can be adopted when the density-based airspace proposed by Duchamp [26] is assumed. The considered factors are traffic densities, minimum separation, and conflict detection and resolution capabilities. For fully mixed free-flight airspace, the risk-based approach can be implemented by modelling a disk around the UAS with an *r* representing the safety zones around the UAS. The airspace is divided into three-dimensional grids where cell-based geofencing is applied when the disk occupies such cells. The model makes use of graph theory and Bron–Kerbosch algorithm for clique calculation [155]. However, the grid size estimation process is not clearly defined.

3.3. CNS infrastructure and performance metrics

A summary of applicable metrics which quantify the CNS performance is provided in Table 6. The framework addresses the requirements of offline planning and online airspace management. The following subsections are meant to provide a high-level overview of key CNS-related factors relevant to the establishment of AAM and UTM services. An in-depth discussion of all relevant CNS technologies and associated performance models is beyond the scope of this article and some relevant references are provided to guide readers willing to explore these topics in more details. Section 5 will discuss some of the practical applications of the CNS performance metrics highlighted to support future evolutions of the collision risk assessment framework for LAAM.

3.3.1. Communication systems

UTM communication system comprises two essential components. The first involves data link and Command and Control (C2) communications, forming the backbone for interactions between pilots or remote pilots and the DSS. These communication links are vital for deconfliction negotiations, enabling the real-time exchange of telemetry data, system health updates, and operational instructions. Simultaneously, the second component centers on cooperative communication between aircraft, facilitating the transfer of surveillance data, including aircraft identification and localization. This collaborative network enhances situational awareness, optimizing traffic management and collectively addressing airspace challenges. The dual emphasis on Data link and cooperative communication establishes the aeronautical communication system as a sophisticated infrastructure critical for present-day aviation, fostering not only immediate operational needs but also contributing to the evolution of autonomous systems.

UAM requires communication technologies that can support high-density operations in densely inhabited urban environments [156]. Various UAM applications have different data rate prerequisites. Voice and basic C2 communications are able to operate at lower data rates.

Table 6
CNS Performance metrics.

CNS	Uncertainty Component	Metric	Description
Communication	Transaction time	Human latency	Human latency includes all human operator response time such as LAAM operator decision-making and response time.
		Technical latency	Technical latency refers to datalink latency and control link latency.
Navigation	Position error sources	Position uncertainty (σ)	The standard deviation of the position solution. This is inflated by multiplicative factors to meet accuracy, integrity, and continuity requirements.
		Dilution of precision (only for GNSS)	DOP is a ratio factor in positioning which is calculated from the satellites-receiver geometry.
		Drift rate (dead reckoning system)	Drift stems from errors in acceleration and angular velocity measurement
Surveillance	Transaction time	Latency	The total latency of position information is the delay between the time of applicability of the position measurement and the time of arrival of the ADS-B message for that position.
	Localization	NIC categorization (only ADS-B)	Navigational Integrity Category specifies the integrity of containment radius aligned with horizontal position which then maps to RNP.
		Tracking error (σ)	The standard deviation of the tracking error.

However, remote pilot operation and autonomous technology require higher data rates (up to 100 Mbps) [157]. A reliability requirement of 99.999 % is necessary for navigation and surveillance [158]. In addition to that, due to the fast pace of operations and shorter characteristic distances compared to conventional aviation, UAM requires low-latency communication, as low as 10 ms [159]. Moreover, the dynamic nature of UAM and the abundance of obstacles in urban areas necessitate technologies capable of achieving global connectivity through Non-Terrestrial Network (NTN) communication based on a space-air-ground heterogeneous network that leverages Line-of-Sight (LOS) and Beyond Line-of-Sight (BLOS) communications as illustrated in Fig. 17.

Assuming The communication is based on cellular networks 4G Long Term Evolution (LTE). The adopted wireless cellular network using 4G-LTE technology consists of ground Base Stations (BS) and aerial users [160,161] with the assumption that only 5 % of its bands is reserved for aerial users. Each BS is assumed to be a traditional hexagonal cell [162] with a radius of 0.5 km [163]. These hexagonal cells are spread across the area of interest, Melbourne CBD, with a total number of 90 nodes. Communication latency is defined as the latency of delivering a packet (L). Each node (v_i) at each time slot is randomly selected to be in one of the following three states: transmit, receive, or sleep with the probabilities of P_T, P_R and P_S, where $P_T + P_R + P_S = 1$.

$$L(v_i) = \sum_{(k,j)\in E(i)} L_{p_{S(k,j)}} \tag{1}$$

where L_p is the latency for delivering a packet of each node (s);

$S_{i,j}$ is a number of collision-free time slots;
E(i) is the represented network links within the node transmission area;

The latency for delivering a packet of each node (L_{p_i}) from ith node to sink j is:

$$L_{p_i} = S_{i,j} \times \frac{packet\ size}{throughput} \tag{2}$$

For the simplification of the problem, the minimum $S_{i,j}$ is adopted and can be simplified as denoted in Eq. (3) with the assumption of $P_T = \frac{1}{n_j+1}$ and $P_R = 1 - \frac{1}{n_j+1}$ [164]. We assume that the probability of the per-link packet being successful is the same for all links.

$$S_{i,j} = \left\lceil \frac{log(1-T)}{log(1-\alpha)} \right\rceil \tag{3}$$

where T is guaranteed per-link successful packet delivery probability;

α is $\frac{1}{n_j+1}\left(\frac{n_j}{n_j+1}\right)^{n_j}$

n_j is number of neighboring nodes.
T is assumed to be 0.999, while packet size is 1500 B and throughput is 7.5 Mbps.

This initial analysis overviewed the impact of communication system characteristics on the operational performance and safety standards of future AAM services, thereby informing the design of future data-driven and network-centric systems. For further information, the readers are referred to Refs. [156,254], where a more detailed discussion is provided.

3.3.2. Navigation systems

GNSS range measurement accuracy is well described by aviation standards [165], with Gaussian overbound distributions accounting for various sources of measurement error. These include.

- Satellite Clock and Ephemeris Errors ($\sigma_{clk\&eph}$);
- Ionospheric Residual Error (σ_{iono});
- Tropospheric Residual Error (σ_{tropo});
- Thermal noise and interferences (σ_{noise});
- Multipath ($\sigma_{multipath}$).

The User Equivalent Range Error (UERE) σ_{UERE} is the root sum square of these independent error sources:

$$\sigma_{UERE}{}^2 = \sigma_{clk\&eph}{}^2 + \sigma_{iono}{}^2 + \sigma_{tropo}{}^2 + \sigma_{noise}{}^2 + \sigma_{multipath}{}^2 \tag{2}$$

In addition to the errors in range measurement, accuracy is also dependent on the geometry of the satellites relative to the receiver. The effect of geometry on the accuracy of the solution is parameterized through a number of scalar factors termed the Dilution of Precision (DOP). The Position Dilution of Precision (PDOP) is the most commonly

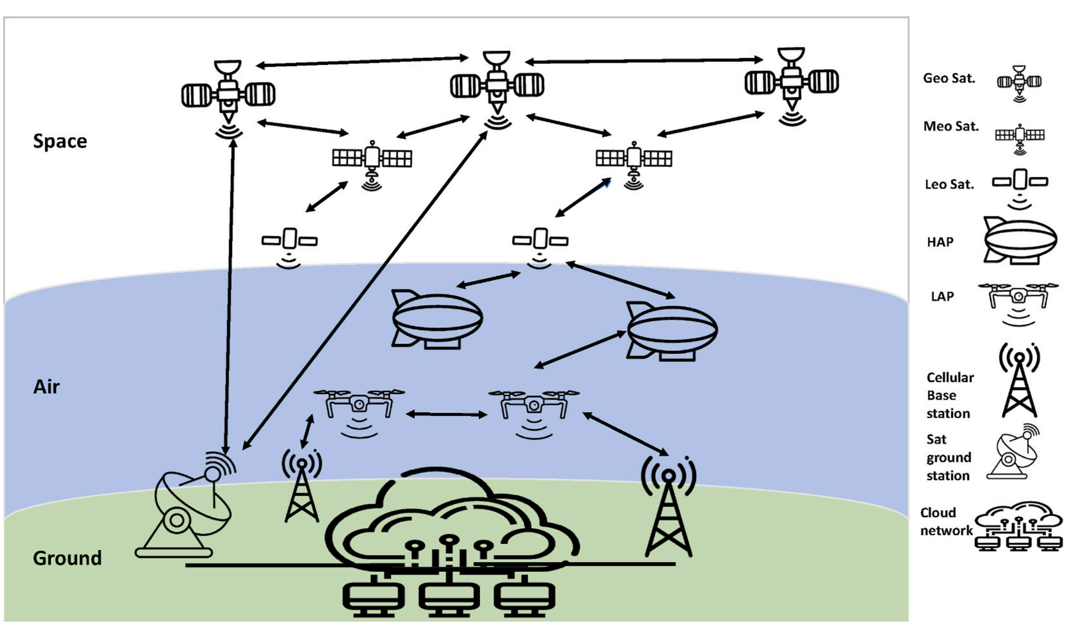

Fig. 17. NTN communication system architecture.

used factor and is presented in greater detail in Ref. [166]. The navigation position error is expressed in Equation (3), showing the relation of σ_{UERE} and PDOP. The maximum errors are chosen to capture the worst performance, representing the conservative case. The covariance matrix of the navigation position uncertainty is presented in Equation (4).

$$\sigma_{NAV,GNSS}{}^2 = PDOP \cdot \sigma_{UERE}{}^2 \tag{3}$$

$$\sigma^2_{GNSS} = \begin{bmatrix} \sigma^2_{xNAV} & 0 & 0 \\ 0 & \sigma^2_{yNAV} & 0 \\ 0 & 0 & \sigma^2_{zNAV} \end{bmatrix} \tag{4}$$

In general, the components of σ_{UERE} are well described by long-standing models in the literature that conservatively bound the error [166]. The only exception is the multipath error component $\sigma_{multipath}$, which is a site-dependent source of error that is difficult to model. However, recent work in the domain is focussing on developing conservative multipath models for UAM given a terrain map and satellite ephemerides [167]. Threshold values on the positioning uncertainty are standardized in conventional aviation operations through so-called 'Alert Limits' [168]. These specify the maximum allowable positioning uncertainty. Since no standards are currently defined for UAM navigation systems, this value is conservatively bounded based on urban canyon width dimensions (since this represents the most stringent performance requirements for UAM use-cases). Therefore, the navigation performance is declared insufficient for $\sigma_{GNSS} \geq W$, where W is the smallest canyon width being traversed for a given planned operation (e.g., this corresponds to W = 25 m for most Australian city centers).

This initial discussion only introduced the fundamental metrics to highlight the role of present-day navigation system characteristics in defining the operational standards and procedures for future AAM services, thereby informing the design of future evolutions. The discussion acknowledged the substantial role of GNSS as primary means of navigation for present-day flight operations, but the literature is already addressing the need to complement GNSS and inertial navigation systems with suitable forms of Vision-Based Navigation (VBN) and onboard augmentation systems to achieve the challenging requirements of navigating within urban canyon and around vertiports. For further information, the readers are referred to Refs. [10,53,166,167], where a much more detailed discussion is featured.

3.3.3. Surveillance systems

As anticipated in Table 6, the uncertainty in the position of a detected intruder aircraft is dependent on two factors. First, the error in localizing the aircraft, and second, the latency between such detection and the position estimate in a downstream separation assurance system. A conventional surveillance scenario is illustrated in Fig. 18. When Primary Surveillance Radar (PSR) is utilized, the estimated range, azimuth and elevation to the intruder aircraft is used to compute its position in a cartesian reference frame. Assuming the reference geometry depicted in the figure, target state vector information is measured relative to the radar site in a spherical coordinate system in range, elevation and azimuth ($r_{RDR}, \eta_{RDR}, \epsilon_{RDR}$ respectively). The measurements in each of the elements are prone to an SNR dependent random range measurement error, which can be calculated as:

$$\sigma^2_{rRDR} = \frac{c}{2B\sqrt{2(SNR)}} \tag{5}$$

where B is waveform bandwidth, c is the speed of light and Signal to Noise Ratio (SNR). Radar angular measurements are commonly made using monopulse receive antennas that provide a difference pattern characterized by a deep null on boresight. The difference pattern formed by these beams may be used to measure the target angular position with a single signal transmission. The measurement accuracy in each angular coordinate is characterized by the RMS of the SNR dependent random angular measurement error, angular bias, and random measurement error. As with the range error, we assume angular error to be normally distributed:

$$\sigma^2_{\epsilon RDR} = \sigma^2_{AN_\epsilon} + \sigma^2_{AF_\epsilon} + \sigma^2_{AB_\epsilon} \tag{6}$$

$$\sigma^2_{\eta RDR} = \sigma^2_{AN_\eta} + \sigma^2_{AF_\eta} + \sigma^2_{AB_\eta} \tag{7}$$

As with the range errors, the SNR dependent error dominates the radar angle error:

$$\sigma_{AN} = \frac{\nu}{k_m\sqrt{2(SNR)}} \tag{8}$$

where: ν is the radar beamwidth in the angular coordinates and k_m is the monopulse pattern difference slope. The tracking covariance is then:

$$Q^{SPH}_{TRK} = \begin{bmatrix} \sigma^2_{r_{TRK}} & 0 & 0 \\ 0 & \sigma^2_{\epsilon_{TRK}} & 0 \\ 0 & 0 & \sigma^2_{\eta_{TRK}} \end{bmatrix} \tag{9}$$

Errors in these measurements propagate to the Cartesian position uncertainty. A more detailed treatment of these errors and the resulting ellipsoid is presented in Ref. [169]. On the other hand, when ADS-B is employed as the primary means of surveillance, the accuracy of localizing the intruder aircraft is closely related to GNSS performance. In addition, the tracking uncertainty ellipsoid must also account for the error due to latency. The total tracking uncertainty $\sigma_{tracking}$ is then:

$$\sigma^2_{tracking} = \sigma^2_{NAV} + \sigma^2_{com} \tag{10}$$

where σ_{NAV} is the uncertainty in GNSS-estimated position, and σ_{com} is the uncertainty due to communication latency.

The overall latency of a SACA process depends not only on the surveillance latency but also on the time required to assess a collision threat and to generate and execute a resolution. In conventional operations, these tasks would have been performed by the pilot and ATC operator. In the LAAM context, however, the bulk of these tasks are assumed to be performed autonomously, with manual intervention required only in emergency conditions.

The total deconfliction time ($t_{SA/CA}$) is the result of the sequential tasks illustrated in Fig. 19, which includes the time taken to process the tracks of intruder aircraft, assess potential collision threats, generate avoidance trajectories and execute them.

Research in trusted autonomous forms of SACA and on the associated evolutions of airborne and ground-based surveillance technologies still has limited maturity though substantial progress is being made. Research into a unified CNS performance-centric formulation of separation volumes has yielded promising results, though the full set of error factors and system specificities is still under study [204,255,256]. Current research priorities include the definition of wake turbulence separation standards for multi-rotor and unconventional AAM vehicles, safely accounting for the rotor wash produced by these vehicles [255]. The reader is also referred to section 5 of this article for the continuation of this discussion from the broader and more comprehensive perspective of collision risk modelling, analysis and management.

3.4. Ground infrastructure

The ground-based support infrastructure comprises a number of vertiports distributed across urban/suburban areas. A vertiport is a structure intended to be used by both eVTOL aircraft and UAS to take off and land. It can be assumed that there will be a mix of vertiports with single or [170] multiple-vehicle support services. Vertiports will be equipped with the necessary infrastructure to recharge/refuel LAAM vehicles between operations. They will be equipped with navigation aids and/or visual cues with corresponding instrument flight procedures to

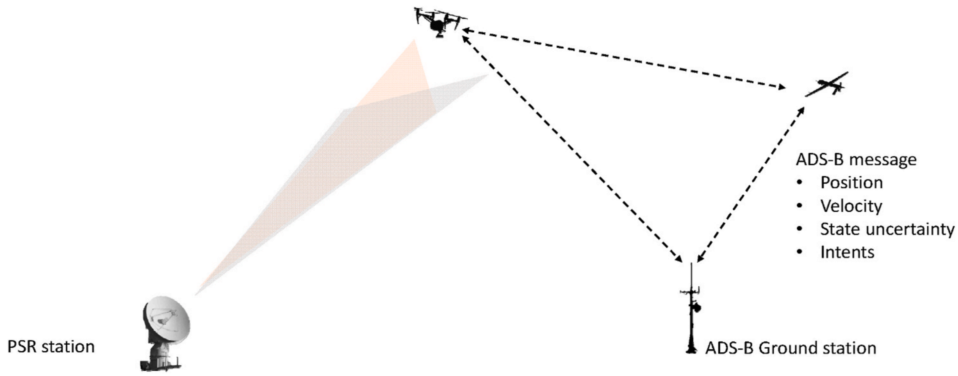

Fig. 18. Conventional surveillance scenario.

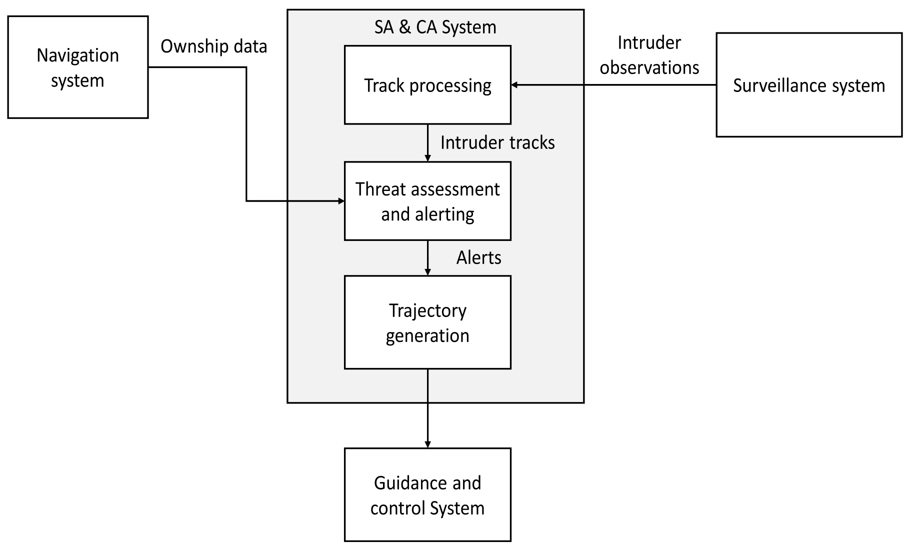

Fig. 19. Overall SA/CA process for autonomous system.

enable safe operations during the night and periods of adverse meteorological conditions. Uniform standards for vertiports do not currently exist and are in different stages of development in many countries. Initial literature reviews and design considerations can be found in Ref. [171] and in the draft FAA advisory circular (150/5390-2D - Draft AC 150/5390-2D, Heliport Design Document).

3.5. Social acceptance

Social acceptance is crucial for the integration of drones into urban environments. The CORUS-XUAM project conducted an extensive review of surveys spanning from 2015 to 2022, providing valuable insights into the social acceptance of drones [131]. These surveys, originating from diverse countries and organizations, were carefully analysed to identify prevalent concerns and formulate effective mitigation strategies. Generally, there is an optimistic tendency towards the social acceptance of drones and UAM, as depicted in Fig. 20. Nevertheless, persistent concerns regarding privacy, safety, and environmental impacts underscore the imperative for ongoing efforts to address these issues and facilitate the seamless integration of drones into urban environments. This section will focus on public perceptions and potential anxieties associated with drone integration and UAM, considering privacy concerns, noise, and visual pollution, all factors for which scholarly research has been conducted, resulting in multiple publications. Other aspects related to contemporary geopolitical developments and military conflicts are intentionally omitted from our review as insufficient research has been conducted to evaluate their social acceptance impacts. The limited technological or scientific implications of these factors also prevents a sufficiently meaningful coverage, but these recent developments are nonetheless having a growing role in affecting social perceptions and are therefore critical for the successful implementation of AAM and LAAM. We therefore acknowledge the need for dedicated social studies, noting that it will be particularly important to investigate the challenges to maintaining public trust in Class 1–2 UAVs as peaceful platforms and on promising strategies for addressing public concerns, including enhanced transparency, improved safety measures, and public education initiatives.

3.5.1. Privacy

Privacy is considered a fundamental right within the European Union, as outlined in Regulation 2000/C 364/01 [172]. The General Data Protection Regulation (GDPR), established in 2016, has standardized the treatment of personal data across Europe. Previous surveys on uncrewed aircraft perception highlighted privacy as a major concern, particularly regarding surveillance missions. However, recent surveys show a shift in focus, with urban applications like passenger transport and last-mile delivery becoming prominent. This change can be attributed to several factors, including the distinct flight profiles of UAM and the prevalence of surveillance cameras in modern cities. The GDPR plays a significant role in reassuring the public about privacy concerns.

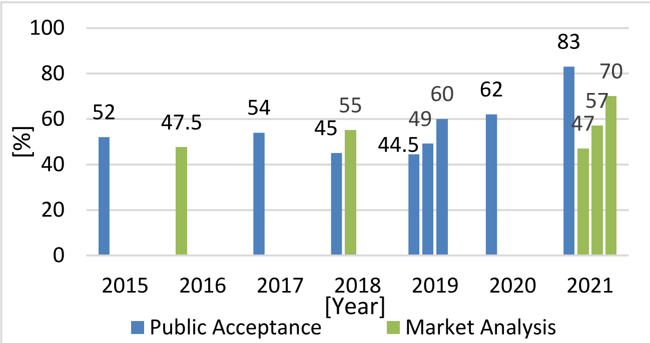

Fig. 20. Drones and/or UAM acceptance levels per survey [131].

Authorities emphasize the need for UAM and U-space to prioritize citizen privacy, aligning with Regulation (EU) 2019/947 [173]. Drone operators are held accountable for privacy violations, and guidelines for responsible drone operations have been established. Measures like privacy by design, pilot visibility, and post-flight data handling are recommended to safeguard personal information [174,175].

3.5.2. Noise

Ensuring acceptable noise emissions from UAM poses a considerable challenge, requiring alignment with the acceptable levels of familiar city sounds. Additionally, factors such as exposure duration and the extent of the population and area affected by noise are crucial considerations in urban environments. Various metrics are used to measure noise, including the long-term average noise level (Leq), the percentage of time noise exceeds the background level (Ln), and the areas and populations impacted by noise above specific thresholds (An and Pn). European Regulation (EU) 2019/945 [170] outlines methods for measuring airborne noise for uncrewed aircraft classes 1, 2, and 3 in Part 13 of the annex. Part 14 mandates that these noise measurements be included in labelling all uncrewed aircraft, expressed as A-weighted sound power levels in decibels (dB). Furthermore, Part 15 establishes noise limits for drones in classes C1 and C2, initially set at 85 dB(A) with allowances for additional noise in heavier vehicles. However, these limits will decrease to 81 dB(A) in the coming years.

3.5.3. Visual pollution

Visual pollution refers to the negative impact caused by the presence of disruptive visual elements and their dynamics in the environment. This phenomenon is typically generated by objects or man-made structures that disrupt the visual harmony of a setting. Notably, UAV flying through urban areas can be categorized as sources of visual pollution. The proliferation of UAV contributing significantly to the degradation of visual quality in our surroundings. The presence of visual pollution is not merely an aesthetic concern but carries notable health-related implications. Moreover, visual pollution can amplify the perception of other environmental pollutants. For instance, the visibility of a noise pollution source can intensify the individual's perception of the noise, fostering a compounded adverse effect. Findings from EASA survey [176] highlight that visual pollution ranks second to last among ten factors considered by citizens regarding UAV deliveries. This places it behind more pressing concerns such as privacy, safety and noise pollution. However, it is crucial to note from the report that visual pollution, although less prioritized, should not be dismissed as inconsequential. Strategies to mitigate UAV visual pollution may include careful route planning to avoid flight paths over open and densely populated areas or flying drones at higher altitudes to minimise their visual prominence [177].

4. Human and machine responsibilities in LAAM

This section builds on the existing body of research and defines the assumed responsibilities of the DSS and operators in the highly automated LAAM environment. In our assumed LAAM operational concept, UAS are autonomously (LoA 9 in the Sheridan scale) carrying out a variety of tasks including separation assurance, collision avoidance, V2V and V2I communication handovers and handshakes, 4D trajectory monitoring and replanning, while being supervised by a RPIC. The overall traffic is managed by an increasingly autonomous LAAM DSS performing a scaled and highly automated ATFM service, while being supervised by an LAAM operator for overall integrity and to amend key decisions only as necessary. Consequently, it is assumed that a single LAAM operator can oversee a large number of LAAM sectors, in a manner not dissimilar to regional ATFM centers. In addition to submitting the initial flight intent to the LAAM DSS [178], the main responsibilities of RPIC are monitoring and controlling the UAS vehicle safety, efficiency, and overall performance [113,179]. DCB and access to airspace are managed by the LAAM DSS, which monitors the current traffic densities and environmental/operational conditions to autonomously calculate demand forecasts and, when D/C imbalances are predicted, determine feasible solutions.

The human operator supervises the LAAM DSS in the semi-autonomous ATFM service (LoA 5 in the Sheridan scale) [180]: thus, overseeing D/C forecasts and supervising the planning, coordination and implementation of ATFM measures required to balance D/C. This is similar to the LAAM DCB service concept proposed by SESAR [50]. The main responsibilities are.

- **Reviewing current situation and forecast:** the human operator reviews the operational safety in terms of CNS and vertiport infrastructure, as well as LAAM system's integrity status within their area of responsibility. The current data and the forecast (incl. uncertainties) need to be reviewed and checked by the human operator;
- **Analyse D/C imbalance:** the human operator reviews the D/C imbalance instances forecast by the LAAM DSS, to establish a coherent picture of anticipated traffic demand. When necessary, the extent and time horizon (where and when) of the expected D/C imbalance are analysed in detail by the human operator with support from the DSS. If necessary, the opportunity of enacting Traffic Flow Management Initiatives (TFMI) is evaluated upfront by the human operator;
- **Selecting a solution:** the LAAM DSS computes and suggests a set of TFMI solutions to the human operator. When necessary, the human operator evaluates and identifies the suggested solutions based on the operational efficiency metrics; therefore, the most appropriate TFMI is selected in a timely manner;
- **Monitoring the outcome:** the human operator monitors the effectiveness of the enacted TFMI and, where necessary, initiates further actions;
- **Responding to emergency and special requests:** emergency and special requests include both infrastructure and vehicle anomalies, as well as requests of any special uses of the airspace. The human operator shall attend these instances and ensure that all affected stakeholders are promptly notified;
- **Coordinating information:** the human operator shall oversee the data exchange (evaluate anomalies in the ATM/LAAM network) and send high-level advisories and notifications as applicable.

It is worth observing that the market is demanding an increasing LoA of these features as well. Notwithstanding, the primary objective of the mission remains to balance the D/C in order to maximise utilisation of the airspace. The secondary objective is to maximise operational efficiency (i.e., minimise total trajectory conflicts per hour), economic efficiency (i.e., minimise total delay time per hour), and environmental efficiency (i.e., minimise total fuel consumption and gaseous/noise emissions per hour).

5. Airspace risk assessment

Adequate Airspace Risk Assessment (ARA) processes for U-space are crucial for ensuring the safe management of uncrewed aircraft operations, particularly in areas where crewed aircraft may fly and over urban regions. ARA, as mandated by the European Commission's Implementing Regulation (EU) 2021/664 [181], evaluates risks related to UAS operations and forms the basis for defining operational requirements and mitigation measures. The ARA involves three key phases: preparation, reference scenario, and assessment [182]. The preparation phase defines the assessment scope and gathers preliminary information, while the reference scenario phase provides a comprehensive overview of the airspace and existing UAS operations. In the assessment phase, safety, security, privacy, and environmental risks are analysed. The resulting Safety Assessment Report, alongside updates to the Concept of Operations (ConOps) and design documents, supports the decision to designate U-space airspace by providing evidence of identified risks and mitigations, ensuring the proposed airspace's safety.

5.1. Specific operating risk assessment

UAS Controlled Flight Into Terrain (CFIT) risk assessment follows the Specific Operations Risk Assessment (SORA) bow tie method to grant approvals for UAS operations. SORA was also adopted by JARUS to perform risk assessments that use a holistic/total safety risk management process to evaluate the risks related to a given operation and then provide proportionate requirements that an operation should meet to ensure a Target Level of Safety (TLOS) is met. This section presents how certain countries implement SORA to mitigate risks for third parties on the ground, considering three types of hazards: fatal injuries to third parties on the ground, fatal injuries to third parties in the air and damage to critical infrastructure [172]. The protection of airspace users, environment, and infrastructure are not considered in this model. The qualitative output (good, adequate and not adequate) of this methodology is calculated from quantitative analysis. The result represents the required level of protection to assure UAS operations safety. Two acceptable levels of safety are set, considering the sheltering factor. The first acceptable level of safety is known as stringent objective E_{C1}; if the result is within this objective, it means that the third party on the ground is safe, and additional protection is not needed. The second acceptable level of safety is standard safety E_{C2}. The trigger occurs when casualty risk per mission R_c is more than E_{C2}, meaning that third party on the ground protection level is not adequate; hence, further actions on modifying technical and operational data and defining limitations and safety barriers are required. If R_c is between EC1 and EC2, the result is adequate, which also triggers minor actions in conditions and limitations specification. The value of E_{C1} (3×10^{-5}) was based on historical accident data between 2009 and 2013 [183]. For E_{C2} value (2×10^{-4}), it is calculated from historical General aviation (GA) accident data (1×10^{-4}) [184,185] multiplied by the mean people on board, which is assumed to be 2.

5.2. Collision risk modelling

Collision risk modelling is a long-standing field of study for conventional aviation. In general, the deployment of new models or proposed updates to existing models occurs at a very slow pace owing to the requirement for extensive verification and validation. As a result, models that were developed as far back as the 1960s are still applied today with modifications and enhancements. The models surveyed for crewed aircraft typically occupy one of the broad categories illustrated in Fig. 21. The most mature and commonly deployed models in practice are analytical models either with a closed-form expression or an integral expression that is evaluated numerically. Of these, the Reich-Marks model [186,187] is the oldest and most widely applied. The model estimates the probability of a mid-air collision between two enroute level flying aircraft. The main objective is the determination of risk associated with lateral separation between adjacent parallel routes or vertical separation between adjacent flight levels. The model applies an ICAO-supported approach and is simple to implement and evaluate. In particular, the model has an extensive history of application in strategic offline scenarios to determine the risk associated with dense routes. The inputs comprise the number of aircraft over an observation period, relative velocities, aircraft dimensions and position error distributions. The model applies a number of simplifying assumptions that make it inapplicable to a broad range of scenarios.

The models that followed were in part developed to overcome some of these limitations. For instance, the Anderson-Hsu model and subsequent extensions [188,189] are applicable to aircraft on both parallel and intersecting routes and can accommodate different navigational performance in cross- and along-track directions for both aircraft. The impact of communication and surveillance infrastructure servicing a pair of aircraft is also more readily incorporated in these models. The improved accuracy and applicability, however, come at the expense of computational run time since the method calls for a multiple-integral expression to be evaluated. Other notable examples of analytical models include [190] in which a geometrical model of the aircraft encounter is used in conjunction with empirical distributions characterizing pilot and controller reaction times. In Ref. [191], nominal aircraft positions were propagated over a tactical timeframe using an assumed kinematic model, and an integral over estimated positions was approximated. In Ref. [192], the probability of vertical loss of separation was computed by estimating altitude distributions through a combination of simulation and real data. The impact of wind forecast uncertainty on conflict probability estimation was investigated in Ref. [193]. Gas models and their generalizations operate on the principle that aircraft behaviour is random like the motion of gas molecules in a container. This is useful in obtaining a conservative assessment of risk where there is little to no historical traffic data. ATC environments without surveillance capability, such as see-and-be-seen Visual Flight Rules (VFR) environments that involve mostly GA aircraft are a prime candidate for this model. Also, surveillance, communication and intervention capability cannot be natively accounted for. Simulation-based techniques apply a markedly different approach to risk modelling. In general, the approach is highly flexible and allows the analysis of a very wide range of causal and complex factors contributing to a collision. Cascading system and personnel failures can be accounted for, which would be highly complex to capture in an analytical approach. Agent-based simulations and Monte Carlo simulations are prime examples of this. Highly realistic scenarios can be constructed and evaluated. However, improved model fidelity is at the expense of computational expenditure. The Traffic Organization and Perturbation AnalyZer (TOPAZ) model [194] is one such example of a highly flexible framework that employs a combination of Agent-Based Models and Monte Carlo simulations to construct and evaluate complex scenarios. Collision risk modelling for UAS is currently an active area of research owing to the growing number of commercial and recreational operations and the prospect of gradually desegregating the airspace. The field of study is not as mature as in the case of crewed aircraft. Nevertheless, several recent models apply methodologies that have been tried and tested on crewed aircraft for decades. For example, in Ref. [195], the probability of mid-air collision was computed using principles related to the collision frequency of gas molecules as embodied in the gas model. Similarly, in Ref. [196], the collision risk between general aviation aircraft and uncrewed aircraft was computed using principles form gas model theory. In Refs. [197,198], a data-driven collision risk model was presented which computed vertical overlap probabilities of crewed and uncrewed aircraft in the proximity of aerodromes. The model is essentially based on the convolution of altitude error distributions for crewed and uncrewed aircraft. Error distributions for crewed aircraft are approximated through kernel

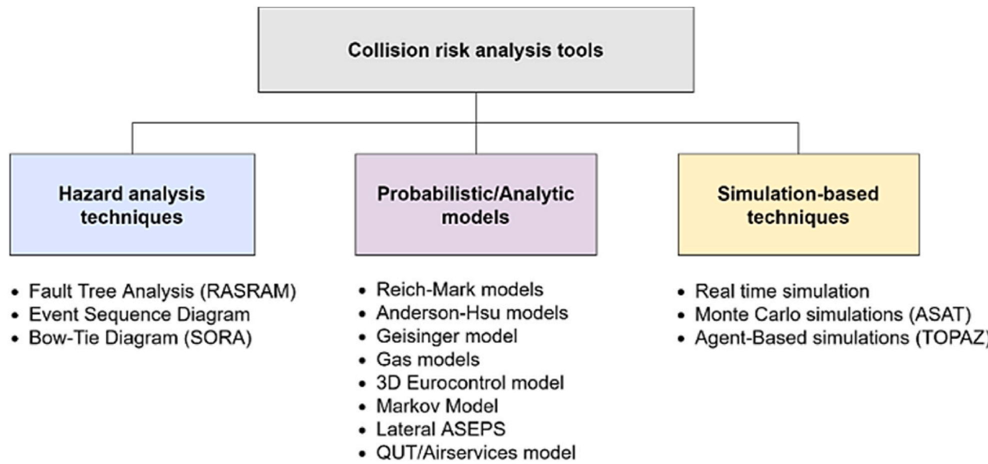

Fig. 21. Ontology of collision risk models.

density estimation applied to radar surveillance data. Vertical collision risk is computed and compared assuming different types of distributions for uncrewed aircraft altitude errors. The model itself has not been validated in an operational setting. However, the underpinning mathematical formulation is based on determining the overlap of distributions, which is a well-established methodology. A methodology based on Monte-Carlo sampling to propagate uncrewed aircraft trajectories was presented in Ref. [199] to evaluate the probability of collision with crewed aircraft in restricted airspace scenarios. A large body of UAS research is focussed on the Detect-and-Avoid (DAA) problem [200], and on the use of radar or active and passive electro-optical sensors [201] for detecting static and dynamic obstacles [202–205]. In general, most of the proposed DAA solutions do not quantify the risk as a direct function of the probability of collision. Rather, a set of metrics and thresholds are defined that serve as proxy variables for defining a collision. For instance, time- and distance-based metrics (tau, modified tau, DMOD) and thresholds are specified for caution and warning alerts in the Minimum Operational Performance Standards (MOPS) for DAA systems that initiate avoidance manoeuvres [206]. This framework was extended in Ref. [207], where a methodology for assuring the integrity and continuity of estimating these metrics was presented. A number of static and dynamic metrics were presented as part of a risk-based framework in Ref. [208]. A key finding that emerges from the review of the prior work is that surveillance and communication performance was not inherently accounted for in the early models. Most early models essentially assumed that aircraft were 'flying blind' (i.e., aircraft on a collision course would remain on the same course with no incorporation of intervention mechanisms). Eventually, as in the case of [188], the capability of triggering an intervention based on the communication and surveillance infrastructure was incorporated in several models. This was typically parameterized in terms of the time required to perform an intervention, quantified on the basis of empirical distributions. Most of the models published so far focussed on the offline planning (strategic) timeframe only (i.e., to drive the design of airspace structures and air routes based on historical traffic data) [209]. In the case of uncrewed aircraft, mid-air collision risk models have a shorter history of development, but typically utilize modelling techniques that have previously been used for crewed aircraft. Since UAS are expected to have greater interactions with general aviation aircraft operating in uncontrolled airspace over the short to medium term, gas model-based methods are popular since they apply conservative assumptions regarding the behaviour of aircraft in the absence of data. A major gap that emerges from the review is that the majority of the traditional models are largely data-driven [209]. This presents problems when assessing the risk of introducing new aircraft (such as UAS), equipment classes and operations. There is no holistic model-driven approach that accounts for CNS performance that is applicable in both offline planning and real-time operational timeframes.

6. Traffic complexity in LAAM

LAAM traffic is highly complex by nature due to the high diversity of missions, speed, flight range, weight class, routing density and CNS performance. In addition, the ability to start/end trips essentially anywhere and the low predictability of traffic has also contributed to the high complexity of this operation [54,138]. Increases in efficiency in the service provision are therefore critical, especially as numbers of UAS/UAM users increase, and this will be dependent on a significant increase in automation and adoption of AI. The UTM report from Cranfield University [210] discussed the benefits of integrating AI/ML in the system and identified the challenges in such integration focussing specifically on the interpretability, scalability, and arbitration of automation. A major barrier to the practical application of AI is the interpretation and explanation of AI/ML algorithms. Particularly in highly safety-critical environments, it is challenging to fully understand why AI algorithms produce a given recommendation. An explanation of how a machine makes its decisions provides insights into how to balance the system's performance, predictability, and explainability. Hence, it is crucial to develop HMI[2] to improve the explanation and interpretation of the expected complex scenarios and the associated AI/ML algorithm recommendations. Moreover, the traffic complexity also impacts the computational complexity of the algorithms since ML-based decision-making techniques require heavy computations to process a large amount of data [211]. Therefore, with mixed UAS and VTOL fleet within low-altitude airspace, LAAM traffic needs to be clustered into groups for problem simplification supporting the human operator's interpretation and lower computational complexity. However, the most viable clustering method for LAAM is still to be determined.

6.1. Cloud-based systems and software architecture

The advancement of LAAM increasingly relies on cloud-based systems and software architecture. Cloud computing offers critical advantages such as scalability, flexibility, and cost-effectiveness, which are indispensable for managing the extensive data generated by autonomous systems [212]. By leveraging cloud resources, LAAM systems can conduct real-time data analysis, facilitate seamless system updates, and integrate with other networked services, thereby fulfilling the dynamic and complex requirements of autonomous operations. The concept of a cloud-based flight management system (CFMS) and its applications in UAM operations was investigated in Ref. [213]. Operating within a cloud computing environment, the CFMS serves as a digital twin of traditional flight management systems, accessing vast amounts of information typically beyond the reach of ground-based aviation systems. This capability enables computational tasks previously considered impractical, supporting functions such as trajectory negotiation, rerouting information exchange, city wind data analysis, and management of unplanned access to controlled/restricted airspace. Moreover, the CFMS facilitates concept validation through laboratory simulations and field flight tests, highlighting its transformative potential in advancing aviation management and operations.

Furthermore, the integration of blockchain technology into cloud-based architectures can significantly enhance the security, transparency, and traceability of data transactions within LAAM systems [212]. Blockchain provides a decentralized framework that ensures the integrity and immutability of data records, crucial for maintaining trust and security across distributed components. This technology supports secure communication, verifies data authenticity, and ensures that all transactions are recorded in a tamper-proof manner. Together, cloud computing and blockchain technology offer a robust infrastructure for optimizing the performance and security of LAAM systems, effectively addressing both operational efficiency and data protection challenges.

6.2. Traffic clustering

Clustering is a commonly used data exploration and dimensionality reduction method in Machine Learning (ML). The objective is to group individuals on the basis of their similarity to each other. The similarity is typically evaluated on the basis of several possible distance metrics. A number of clustering techniques have previously been proposed for traffic flow identification and analysis, specifically where the set of clusters could best characterize an operational traffic flow within the airspace. Such methods relate each cluster to a specific air traffic flow pattern characterized by temporal and spatial features [214]. Various ML algorithms have been studied to cluster both air and ground traffic. In ATM, research in ML clustering has been mainly focussed on the approach and landing phases within the Terminal Manoeuvring Area (TMA) airspace, as summarised in Table 1. A common algorithm used in this context is Density-Based Spatial Clustering of Applications with Noise (DBSCAN). The primary objectives of TMA clustering techniques have typically been to detect anomalies, monitor conformance, optimize take-off and landing schedules and assess runway utilisation [215–218]. On the other hand, the clustering objectives of ATFM are mainly to specify flow pattern variations adopting K-means [219], Gaussian Mixture Model (GMM) [220], and Hierarchical DBSCAN (HDBSCAN) [214]. K-means clustering is widely applied due to its fast and simple implementation [221]. Supervised ML techniques have also been investigated [222], but widespread adoption is hampered by the limited availability of labelled datasets. The advantage of DBSCAN is that the model is suitable for noisy data as it is more robust in the presence of outliers. However, as in the case of GMM, it is not suitable for datasets with high dimensionality and is limited to 2D data. HDBSCAN is an improvement of DBSCAN with an improved ability to manage clusters of varying densities [214]. Other applications have implemented swarm intelligence and self-organization as part of the clustering method [223]. A common strategy for traffic clustering is to reduce data dimensionality upfront. As a preprocessing phase, it projects high-dimensional data onto a lower-dimensional space and uses it as an input to the clustering algorithms. Several techniques have been implemented in the field such as principal component analysis [216], autoencoders [224], and the t-distributed stochastic neighbour embedding (t-SNE) [220,225], which are captured in Table 7.

In LAAM, the most viable clustering method is still to be determined. Hence, it is of paramount importance to identify the most effective and versatile clustering methodology to implement in the highly automated low-altitude airspace management framework. Moreover, the diverse characteristics of LAAM operations, such as mission types, weight classes, and, specifically, CNS capabilities, are all important factors that heavily impact the DCB management [50,178]. Hence, considering only 4D-Trajectory (4DT) parameters as is common in the literature is not optimal in LAAM, especially for UAS traffic clustering. Based on the SESAR DACUS project [50], CNS factors are important to establish the capabilities, manoeuvrability and position of UAS in 4D space. CNS performance therefore must be included as part of the feature vector in the clustering algorithm as it is a critical factor in ensuring the safety and efficiency of operations in any given airspace volume and is, therefore, essential for LAAM airspace. Following these considerations, a clustering approach that exploits CNS performance and mission factors to adequately address the LAAM operational context appears as a promising solution. The characteristics of the data and problem need to be understood and accounted for to choose a good clustering algorithm for such an application. Various clustering requirements need to be considered: scalability, ability to deal with different types of attributes, the discovery of clusters with arbitrary shape, requirements for domain knowledge to determine input parameters, ability to deal with noisy data, incremental clustering, and insensitivity to input order, the capability of clustering high-dimensionality data, and interpretability and usability. It is important to note that existing clustering techniques only address some of the requirements; hence, based on the problem and characteristics of the LAAM traffic, some requirements need to be prioritized over others in a compromising manner in certain magnitudes. Clearly, viable LAAM traffic clustering technique will have to deal with a large number of dimensions and a large number of data points; leading to high computational complexity. Also, a methodology for integrating performance-based clustering algorithms with the TFMI determination process will be required. To guarantee that this clustering

Table 7
Summary of traffic clustering methods.

Application	Objective	Method	Key features	Ref.
TMA	landing schedules optimization, outlier detection	DBSCAN	4DT	[215]
TMA	Conformance monitoring	PCA + DBSCAN, K-means	Waypoint	[216]
TMA	Anomaly detection, runway utilisation assessment	HDBSCAN	4DT and wind speed	[217]
TMA	Trajectory prediction and anomaly detection	HDBSCAN	horizontal spatial data (latitude and longitude)	[218]
ATFM	Flow identification	HDBSCAN	3DT, speed, heading	[214]
Approach landing	Outlier detection with a focus on energy management	DBSCAN	4DT glide angle ground speed and rate of descent	[226]
ATFM	Large dataset handling, Flow identification	t-SNE + DBSCAN, Gaussian Mixture Model	4DT	[220]
TMA	Trajectory conformance assessment against identified flows	DBSCAN, Random forest, K-means	horizontal spatial data (latitude and longitude)	[227]
ATFM	Complexity estimation and flow optimization	K-means	Speed and route	[219]
TMA	Flow identification	K-means	Waypoint and speed	[228]
TMA	Runway recognition	Supervised models	4DT	[222]
Approach landing	Flow identification	Autoencoder + Deep Convolutional Embedding Clustering	4DT	[229]

approach can be adopted in the envisioned LAAM scenarios, the following key attributes will have to be evaluated.

- **Versatility** – the clustering methods need to be suitable for different types of data such as numerical and categorical data to support the proposed multi-criteria performance-based clustering approach. The clustering effectiveness in terms of population sizes is used to evaluate versatility. Moreover, a time-dependent versatility can also be evaluated from CNS performance parameter variations;
- **Scalability** – as the amount of traffic increases, scalability becomes a crucial factor in LAAM operations. Therefore, clustering algorithms should allow for variable trade-off between computing time and quality of the resulting clusters so as to be scalable with either large or small traffic volumes.

7. Artificial Intelligence algorithms in LAAM

Given the anticipated levels of automation required, achieving trusted autonomy is a key objective to accommodate a safe growth of LAAM operations. The development of highly automated systems leveraging AI algorithms for tasks such as anomaly detection, pattern identification, accurate inference, and optimal conflict resolution is not only technically feasible but has demonstrated significant potential. However, the opaque nature of AI algorithms limits their usability, as the lack of interpretability and explainability restricts trust in these systems. This is particularly challenging in aviation applications where safety and reliability are paramount. To overcome these challenges, AI-based DSS in LAAM are expected to incorporate eXplainable AI (XAI) to enhance the interpretability and transparency of system reasoning, thereby building trust among human operators. This section explores the application of evolutionary and hybrid algorithms in LAAM operations, highlighting their potential and the importance of integrating XAI to achieve certification and operational reliability. Mainstream AI techniques include Neural Network (NN) based ML approaches, whichare intentionally omitted from the discussion here given their vast coverage in numerous contemporary publications. The readers are referred, for instance, to the following references within our group alone, which feature comprehensive reviews of ML methods pertinent to LAAM vehicles and to their operations [257,258]. The following sub-sections provide a brief outline of other AI techniques, less covered in the mainstream literature, and of some of the most promising XAI approaches from the LAAM implementation perspective.

7.1. Evolutionary computation

Evolutionary algorithms are stochastic methods that utilize random processes to search for solutions. Among the most prominent evolutionary algorithms are Genetic Algorithms (GA) and Differential Evolution (DE), both of which are grounded in evolutionary theory [230]. In contrast, Particle Swarm Optimization (PSO) algorithms draw inspiration from the behaviour of insect swarms in nature [230]. A significant advantage of these algorithms is their independence from the problem's structure, allowing their application to a broad spectrum of complex problems, including those that involve simulations or experimental models. In the context of LAAM operations, evolutionary algorithms are particularly effective in optimizing path-planning problems, leading to enhanced route efficiency, reduced fuel consumption, and improved operational safety [231,232]. By efficiently exploring expansive solution spaces, these algorithms can identify optimal or near-optimal configurations that would be impractical to determine using conventional methods.

7.2. Hybrid algorithms

Hybrid algorithms combine the strengths of multiple AI techniques, thus overcoming the limitations of individual methods and leveraging their complementary capabilities. In LAAM operations, hybrid algorithms often combine evolutionary algorithms with other AI techniques to optimize DCB and enhance decision-making. This approach is particularly beneficial for addressing the multi-objective and multi-constraint optimization challenges inherent in LAAM. For example, in Ref. [233], a Deep Q-Learning Network (DQN) combined with a Genetic Algorithm (GA) was proposed to determine the optimal DCB for dense LAAM. Additionally, a hybrid Tabu Search (TS) and A-star (A*) path planning algorithm, which enables dynamic route planning for all UAS in densely operating airspace, was presented in Refs. [233,234,259].

7.3. AI explanations

Most AI and particularly NN-based ML models lack the explainability of the algorithm itself and the output results, thereby challenging the human operator to understand and accept such a solution. Henceforth, XAI techniques are a key aspect in LAAM research to ensure a safe and effective AI integration. According to Arrieta et al. [235], the XAI domain is systematically analysed, and its alternative techniques are classified in two consecutive stages, as shown in Fig. 22.

The first classification subdivides XAI approaches between interpretable models and post-hoc explainability, thereby distinguishing AI algorithms based on their inherent/inbuilt transparency. When the AI/ML models cannot produce a transparent explanation natively, a dedicated post-hoc analysis is needed to explain their decision so that the second class of XAI methods is required. Model-agnostic post-hoc explanation methods can be applied to any AI/ML model; whereas model-specific methods are developed only for a specific AI/ML model and will not work in conjunction with other techniques. Generally, black box ML algorithms will require a post-hoc explanation method. Moreover, there are two types of explanations: global and local. The local explanation divides the complex model into simple individuals, while also analyzing the individuals' relationship. The global explanation offers an overall understanding of the algorithm, aiming to make the entire decision-making process completely transparent and comprehensive. Usually, it is necessary to utilize these two explanation methods simultaneously to explain the algorithm, which can effectively reduce the understanding bias caused by a single method.

Due to the opacity of black-box models, post-hoc explanation approaches are essential to interpret the predicting model and its results. However, a single explanation method limits and biases the interpretation and understanding of the black-box model. Therefore, two or more different post-hoc explanation models should be used to simultaneously explain a black-box algorithm and prediction results, thereby enhancing the interpretability of predictions. In recent research, the post-hoc explanation models that were successfully used were SHapley Additive exPlanations (SHAP) and Local Interpretable Model-Agnostic Explanations (LIME). SHAP is a visual local explanation method for tree models. While assigning the weight and value to each feature, the local explanation is extended to capture the features' interaction directly, and a large number of local explanations are used to understand the global structure. Besides, SHAP built-in visual components can intuitively display the influence of complex combinations of predictor variables [236]. The LIME model can be completely unaffected by the model itself but only explains the results. In other words, LIME can explain any model without requiring its adaptation. These two models are supported by XGBoost that aims to further explain the prediction results in more detail and highlight the driving factors of the results.

8. Future LAAM developments

The future development of LAAM systems will face significant challenges in verification, qualification, certification, cybersecurity, and trusted automation. As these systems integrate advanced AI, ensuring AI explainability, reliability, and consistent performance will be crucial. Cybersecurity threats such as data interception and manipulation will

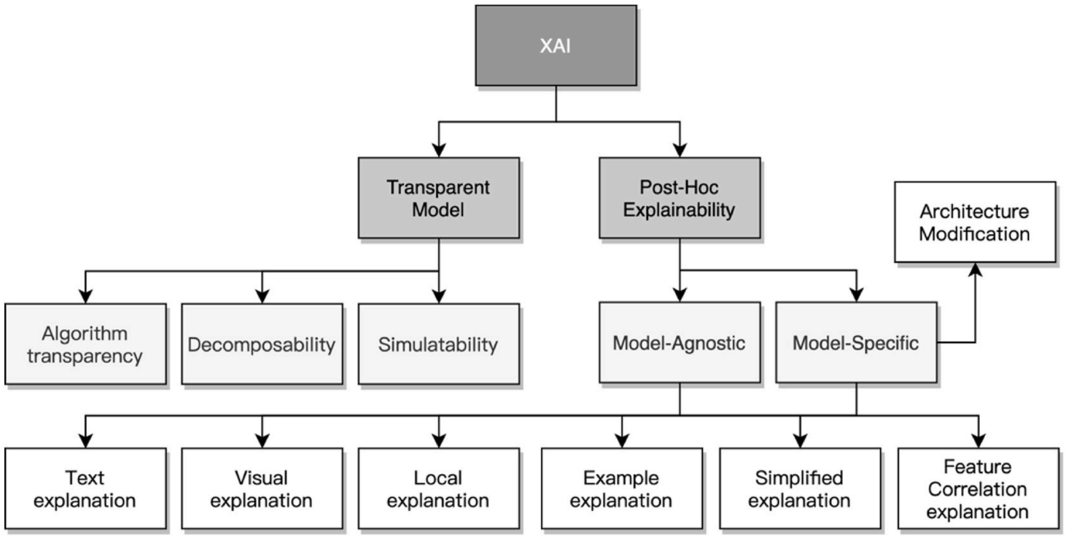

Fig. 22. Classification of XAI methods.

necessitate robust security measures. Additionally, achieving trusted automation will require the incorporation of XAI to provide transparency in decision-making and $CHMI^2$ to dynamically adapt to operators' cognitive states. Addressing these future challenges is essential for the effective deployment and widespread acceptance of autonomous systems in LAAM.

8.1. Verification, qualification and certification challenges

The next major challenge for LAAM system development is certification in real-world implementation applications. The proposed LAAM systems are mostly embedded with several AI features. AI techniques allow the proposed system to adopt higher LoA and advanced functionalities, which are different from how the traditional aerospace industry has operated. However, various challenges are posed by integrating AI in avionics systems: testing, evaluation, performance and safety assessment for certification. The explainability and interpretability of different methods are the key challenges, especially for human operators and human-machine coordination. This challenge also ties in with the reliability of AI methods – the system should provide the same set of solutions under the same environmental conditions. The high security for operational systems emphasize the importance of the cybersecurity perspective, including protecting all elements in the operations. Future research should address the three key cybersecurity elements: privacy, authentication, and authorization. Hence, the Verification/Qualification, Validation and Certification (VV&C) of systems incorporating AI techniques all become a crucial step in the systems engineering process. EASA has developed and published a report containing their latest guidelines for certification of intelligent systems; however, details of specific use cases or how the realization becomes practice still need to be defined in more detail. To support this transition, the $CHMI^2$ system can be one method to assist VV&C of systems through HITL experiments by using the human operator's performance and cognitive states as a baseline.

In this context, the emergent cyber-physical-social system characteristics of LAAM elicit the introduction of new VV&C methodologies that capture the reciprocal dependencies of human operators and highly automated systems [47].

8.2. Cybersecurity

UAS and other AAM vehicles encounter diverse cybersecurity threats that pose substantial risks to their operations and the integrity of the UTM system [237]. These threats encompass data interception, manipulation, and jamming, exploiting vulnerabilities across communication, navigation, surveillance, and ground networks [238–240]. To counteract these risks, a spectrum of traditional and sophisticated mitigation techniques is proposed. Classic methods such as spread spectrum techniques, intrusion detection systems, and UAS auxiliary communication systems offer foundational security measures [241–243]. Additionally, advanced mitigation approaches leveraging machine learning algorithms, including supervised learning techniques like support vector machines and artificial neural networks, along with unsupervised learning algorithms such as generative adversarial networks and reinforcement learning algorithms, provide enhanced defence capabilities [244–246]. Nonetheless, the practical application of machine learning algorithms presents inherent challenges, including adaptability to varying environments, adequacy of training data availability, and the interpretability limitations of black-box models. Overcoming these challenges is pivotal to achieving optimal detection performance, characterized by high detection rates and minimal false-positive and missed detection occurrences. Moreover, amidst the escalating cybersecurity landscape, marked by a growing threat of cybercrime in low-altitude ATM and UTM domains, fortifying cybersecurity measures emerges as imperative to safeguarding the reliability and security of UAS and UTM systems.

CPSS attributes of LAAM introduce further complexity from the security perspective as all entities of the system can be targeted by attacks, potentially affective the entire network.

8.3. Towards trusted autonomous systems

A trusted autonomous system is characterized by its reliability, safety, transparency, effective human-machine interaction, accountability, and ethical alignment. Achieving trust in LAAM systems requires the integration of XAI and $CHMI^2$ [44]. In particular, XAI enhances system transparency by elucidating the decision-making processes of autonomous systems, thereby fostering user trust and understanding. This transparency is essential for users to comprehend and trust the system's actions, particularly in complex operational environments. Concurrently, $CHMI^2$ improves human-machine interaction through dynamic adaptation based on the operator's cognitive states, such as situation awareness and mental workload. This adaptive interaction ensures that the system can respond to the operator's needs and maintain optimal performance levels. The design of $CHMI^2$ must be grounded in thorough task analysis. Task analysis helps in understanding the demands placed on both the human operator and the system, ensuring that the interface supports efficient and intuitive interactions. Additionally, system and human operator integrity metrics are crucial for determining the optimal level of autonomy and dynamically allocating tasks within the Human-Machine team. These metrics ensure that both the system and the operator maintain their integrity and functionality, enhancing overall system performance.

The combined application of XAI and CHMI^2 facilitates the development of reliable, efficient, and user-centric autonomous systems in LAAM, addressing both operational transparency and human factors. The integration of high-performance AI necessitates advanced human-machine coordination, incorporating enhanced monitoring and augmentation functions to ensure both machine and human integrity. Furthermore, the transition from HITL to HOTL represents a supervisory control paradigm where an operator focuses on high-level strategic tasks while automated and intelligent systems perform most or all tactical-level activities. This paradigm embodies trusted autonomy, allowing AI to prevent or mitigate imminent hazards without requiring the operator's immediate approval, unlike HITL operations. However, the human operator remains informed and consulted, retaining the ability to intervene if necessary. The integration of Explainable AI and CHMI^2 technologies in LAAM is essential for developing systems that users can trust to operate safely, efficiently, and transparently. By addressing both operational transparency and human factors, these technologies pave the way for the widespread adoption and acceptance of autonomous systems in various domains.

9. Towards Multi-Domain Traffic Management

Beyond LAAM developments, recent research is tackling the longer-term need to integrate all flight domains (i.e., low-altitude, conventional/controlled and high-altitude above FL600). Such a MDTM framework would support the safe, efficient and sustainable operation of all current and likely-future aerospace vehicles, thereby encompassing the widest variety of crewed/uncrewed aircraft and space-faring vehicles. Importantly, the High-Altitude Operations (HAO) context will see a proliferation of stratospheric/High-Altitude Pseudo Satellites (HAPS), supersonic and hypersonic vehicles, point-to-point suborbital transport vehicles. All of these vehicles and a growing number of space launch and re-entry operations are required to transit through low-altitude and conventional airspace regions, thereby making legacy segregation-based approaches unsustainable when traffic volumes increase. Fig. 23 illustrates the envisioned evolution and progressive integration of conventional and autonomous platforms within a MDTM framework. This transformation will entail intermediate steps such as the possibility for one or multiple ground/airborne pilots to supervise multiple air vehicles, in line with the so-called N-to-M paradigm [247–249].

9.1. Current MDTM developments

Similarly to the far-fetched LAAM vision but extending to other airspace regions, the fundamental long-term objective of MDTM is to abandon the traditional approaches based on segregation and operational restrictions, by establishing a network-centric operational environment where the management of airspace demand/capacity and separation requirements can be accomplished in a safe and efficient manner for all possible aerospace users [250–253]. The flexible and adaptive allocation of airspace resources that MDTM shall feature based on real-time demand can be seen as an extension of the Dynamic Airspace Management (DAM) paradigm. AI-based analytics and DSS will facilitate the optimization of airspace access allocation, while also supporting the transition from human-in-the-loop to human-on-the-loop paradigms.

Significant research efforts are required to realize the MDTM vision: the consideration of the widest variety of current and envisioned aerospace vehicles in the study of mixed-use airspace operations will support the development of new separation methodologies, likely based on a unified and versatile analytical framework which considers relative dynamics, manoeuvrability and handling qualities in a realistic set of

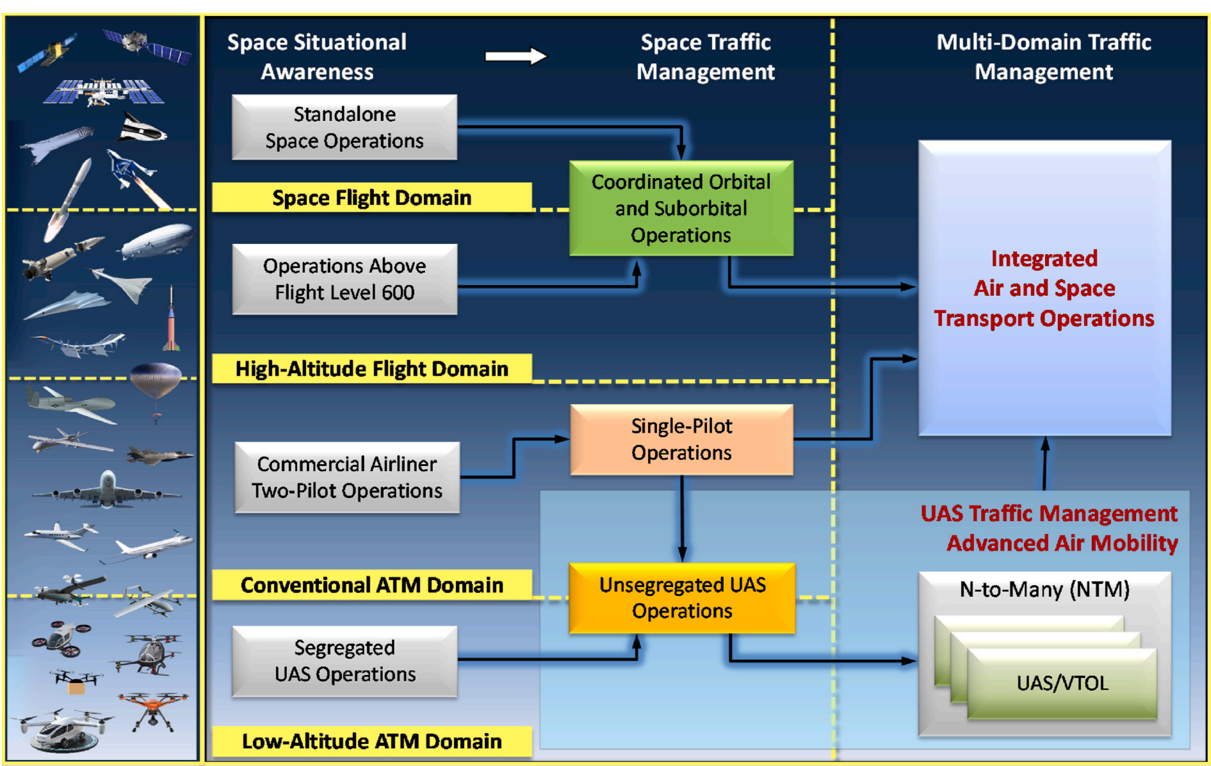

Fig. 23. Evolutions towards a MDTM framework.

atmospheric conditions. The full implementation of the PBO paradigm for all CNS systems is indispensable, as such diverse aerospace platforms will necessarily rely on different equipment. Suitable levels of automation and new forms of human-autonomy teaming will have to be introduced for all the ground-based supervisory operators, both in vehicle operation (flight crew) and in airspace management roles. The integration of Space Traffic Management (STM) services will be required to ensures an effective coordination and safety of activities within both the atmosphere and the near-Earth space, since both atmospheric and space weather and traffic conditions need to be considered in the planning of operations. This also calls for an adequate implementation of multi-domain traffic and weather surveillance systems. Significant standardization and regulatory advances are needed, starting from filling the gap in the jurisdictions of United Nations entities: ICAO is currently restricted to FL600, while the United Nations Office for Outer Space Affairs (UNOOSA)/Committee on the Peaceful Use of Outer Space (COPUOS) coordinate international harmonization only above the Karman line (about 100 km from the surface of Earth). The necessary technological developments and evolutions in certification requirements will require support and contributions by a significant number of stakeholders.

9.2. Towards a cyber-physical-social system

Similarly to avionics systems onboard aircraft, the conventional ATM infrastructure has progressively evolved into an integrated Cyber-Physical System (CPS), i.e., one where hardware and software seamlessly participate in the provision of the service and are essential to the mission success. However, a fundamental difference emerges when extending the analysis to the human operators in the overall service provision: conventional avionics systems are designed considering one or multiple pilots for the achievement of safe and efficient flight management, leading to an optimal Cyber-Physical-Human System (CPHS) integration [44]. In CPHS, the focus is not only on operational/technical capabilities but also on attaining optimal human interactions. This approach is crucial in properly addressing the requirements of increasingly diverse vehicles, operational and environmental conditions, while also retaining aircrew preparedness and ensuring skill retention for maximised chance of success in all possible conditions.

On the other hand, even at a relatively local level, the ATM services have historically pertained a multitude of human operators, often separated geographically over large areas. Thus, for several decades, ATM modernization efforts have been focussing on enhancing the efficiency of this large networked system, mostly by improving the digital infrastructure [48]. In this context, continuous improvements in the communication network capabilities have contributed to enhance collaboration among human operators over wide areas. However, it was not until recently that ATM modernization initiatives have started venturing into the social dimensions, aiming at a more efficient involvement of other key ATM stakeholders, including airlines and airport operators. The Collaborative Decision-Making (CDM) concept and its recent evolutions revolve around these high-level objectives [134].

Based on these premises, it is evident that the network-centric characteristics of future ATM (e.g., MDTM) makes it necessary to consider evolutions in human-machine teaming beyond the individual human operators (i.e., CPHS philosophy), as this would potentially result in each operator working in a disjoint and highly suboptimal manner across the network. To address these challenges, current research efforts are focussing on Cyber-Physical-Social System (CPSS) architectures, where a multitude of human operators and stakeholders, spread over large geographic areas, are involved in the design, operation and evolution of MDTM systems. Fig. 24 depicts the relationships between CPS, CPHS and CPSS, illustrating how each system concept encapsulates and expands upon the one preceding it, progressively integrating the social dimensions.

In the context of MDTM systems conceptualized as a CPSS, it is imperative for the design and operational strategies to thoroughly integrate social interactions. Accordingly, innovative systems engineering methodologies must be devised to comprehensively cover Design, Development, Test, and Evaluation as well as Operations (DDTE&O) throughout the entire lifecycle of CPSS. These methodologies must ensure that systems are not only technically sound but also acutely responsive to the complex social dynamics present in modern airspace/traffic management. This involves implementing stakeholder analysis, human-centered design, social impact assessments, and collaborative design processes to foster better cooperation among air traffic managers, policymakers, and users. Additionally, these systems should integrate ethical and regulatory compliance and provide for continuous training and adaptive features to accommodate evolving social norms. By adhering to these principles, the emerging CPSS engineering methodologies will enhance the operational efficiency and adaptability of MDTM systems, thereby leading to more robust and effective traffic management services, handling the complexities of increasingly congested and interconnected transportation networks.

Given these new comprehensive requirements, there arises a clear need for a new engineering model that could be based on an integrated digital twin framework—simultaneously addressing the cyber, physical and social aspects of the system DDTE&O. This new model would incorporate verification and validation at every stage of the MDTM development process, ensuring that the cyber, physical and social elements of the system are developed and refined in parallel. This holistic approach not only promotes a forward-looking strategy but also ensures that the system is adaptable to future challenges and advancements in air and space traffic management. Such a model is crucial for ensuring that future DSS for MDTM are not only safe, efficient and robust but also aligned with societal needs and ethical standards, effectively managing the interplay between the cyber-physical elements and the complex social dynamics that drive the overall system performance, behaviour, and evolutions.

10. Conclusions

The emerging paradigms of Uncrewed Aircraft Traffic Management (UTM) and Advanced Air Mobility (AAM) mark a significant

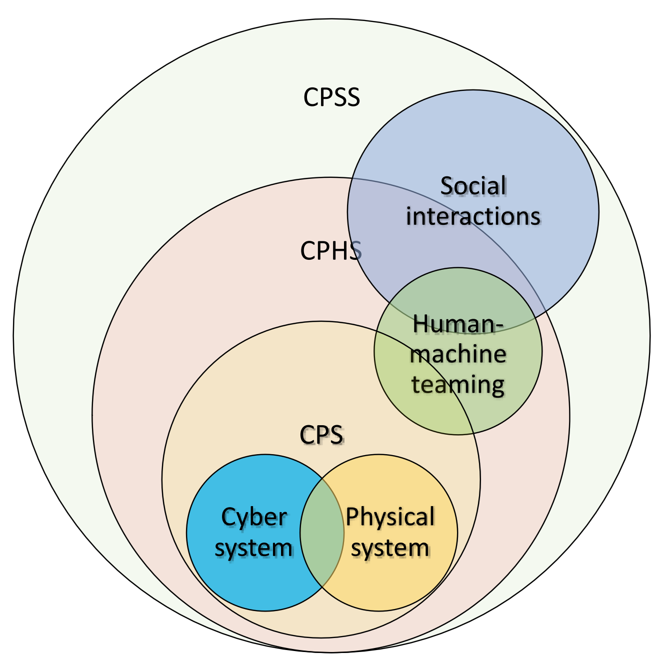

Fig. 24. The evolution of cyber-physical systems.

advancement in managing low-altitude airspace, particularly in urban and suburban areas experiencing increasing demand for air transport services. Traditional airspace management approaches are inadequate for these dynamic environments, necessitating the development of an integrated Low-Altitude Airspace Management (LAAM) framework supported by new flight systems and infrastructure. Both airborne and ground-based decision support systems will require a seamless integration of cyber, physical, and human elements to enable flexible and robust airspace management. Technologies such as adaptive automation and Artificial Intelligence (AI) will play a key role in facilitating real-time decision-making, particularly in tasks such as Separation Assurance and Collision Avoidance (SACA), thereby enhancing safety and operational efficiency. This article has explored the challenges associated with the implementation of a LAAM service accommodating a wide diversity of vehicle types, as well as the key role of such a framework in support of a safe and commercially successful AAM. The analysis of existing vehicle and airspace design concepts highlighted the need for specialized routing solutions to integrate safely with the existing airspace structure in the near term. A major focus was on the development of an adequate LAAM Concept of Operations (CONOPS), which in addition to outlining the roles of human operators in the service provisions, substantiates the required evolutions in Communication, Navigation, Surveillance and Air Traffic Management (CNS/ATM) infrastructure and operational regulations to integrate Uncrewed Aircraft Systems (UAS) and other AAM vehicles safely and efficiently into the airspace. The review also addressed the challenges associated with increased traffic density and operational complexity, which deserve careful consideration to facilitate smooth integration into urban and suburban environments while fostering public trust in the AAM services. The evolving roles of human operators in LAAM were discussed, noting a major shift from manual to supervisory responsibilities. However, this ongoing transformation is still to be reflected by a detailed specification of roles and responsibilities that will be ultimately captured by future aviation safety standards. In this context, the development of effective Human-Machine Interfaces and Interactions (HMI^2) and adaptive/cognitive forms of HMI^2 is crucial for ensuring that automation effectively complements human oversight at all times, preventing dangerous instances of overload. The main challenges and potential solutions concerning social acceptance of AAM were also outlined, particularly in terms of noise, privacy, and visual pollution concerns.

Substantial evolutions of the CNS/ATM infrastructure are deemed essential to maintaining operational safety and efficiency within the LAAM framework. In this context, the communication network requirements for AAM prompt a transition to Non-Terrestrial Networks (NTN), which integrate Line-of-Sight (LOS) and Beyond-LOS (BLOS) technologies. NTN datalinks are in fact essential for ensuring reliable connectivity, overcoming urban obstacles, facilitating continuous data exchange, and maintaining situational awareness and operational safety. Based on these premises and considering the foreseen evolutions of all airspace domains (i.e., low-altitude, conventional/controlled and high-altitude above FL600), the article also outlined the opportunities and challenges associated to a possible Multi-Domain Traffic Management (MDTM) framework. The introduction of such unified framework would contribute to maximise operational efficiency and safety in a consistent and globally harmonized manner. The envisaged MDTM framework would support all current and likely future aerospace vehicle operations, including crewed/uncrewed aircraft and space-faring vehicles, with due consideration of their mission specificities and the resulting traffic complexities. The successful deployment of an MDTM framework will however require evolutions in both CNS/ATM systems, operational regulations and certification standards, aimed at establishing an acceptable level of situational awareness, real-time demand/capacity management and effective SACA capabilities. These, in turn, will require the full implementation of the performance-based CNS operational framework, advancements in human-autonomy teaming, and the further evolution of automation levels. The successful implementation of LAAM and its integration into a cohesive MDTM framework will also requires advancements in systems engineering processes and methodologies to reflect the Cyber-Physical-Social System (CPSS) nature of this framework.

Significant challenges are still hindering the development of LAAM systems, including verification, qualification, certification, and cybersecurity assurance, as well as implementing trusted forms of automation. In particular, the airworthiness certification of AI-based systems for real-world aeronautical applications is a major area of ongoing research and requires substantial advances in diverse areas such as reliability, explainability, and performance consistency. Addressing cybersecurity threats such as data interception and manipulation requires robust strategies across ground-based and airborne systems. Achieving trusted automation is a challenge extending beyond the mere certifiability and cybersecurity of automated systems. The most promising solutions on this front include the adoption of explainable AI for transparency in decision-making and of adaptive forms of HMI^2 to better match operators' cognitive states. Addressing all the outlined challenges will allow the development of reliable, efficient, and user-centric LAAM and MDTM services that support safe and sustainable operations in low-altitude airspace, thereby achieving the widespread acceptance and commercial success of AAM.

CRediT authorship contribution statement

Nichakorn Pongsakornsathien: Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Nour El-Din Safwat:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis. **Yibing Xie:** Writing – original draft, Visualization, Software, Investigation. **Alessandro Gardi:** Writing – review & editing, Supervision, Software, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Roberto Sabatini:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

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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Data availability

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

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