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Whitepaper on the Automation of the Airspace Environment

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Abstract

This document in its draft version is internal to JARUS. It is intended to provide an outline for considering the impact of automation across all aspects of aviation safety, while providing considerations for further developing the future of automation roll-out across the airspace. The scope is limited to safety aspects and does not specifically address broader issues related to liability, cost, or legal authority as these must be interpreted through local customs including the legal system, history, cultural practices, and public acceptance of risk and liability.

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EXECUTIVE SUMMARY

The JARUS Automation Work Group began its work with the continuing development of an automation concept, building upon the initial work of the former Concept Development Work Group. During the early development work, the work group soon discovered the many, interactive considerations for automation in the airspace environment. This paper highlights the complex nature of automation in aircraft, airspace and air traffic service provisions within the airspace environment. The paper is intended to enable other JARUS work to make recommendations for operations, airworthiness and safety risk management with a common understanding of the challenges to be addressed as one or more of these elements in the airspace environment become increasingly automated. This whitepaper does not redefine the existing three-category JARUS Operational Concept, but it does offer new considerations for operations in each category as the airspace environment becomes more and more automated. Increasing automation of the airspace environment may occur in each operational category and recommendations for the technical, safety and operational requirements for the safe integration of UAS into airspace and at aerodromes are useful for all operations.

This paper addresses automation in the airspace environment from four perspectives. First, flight rules, where the paper notes how flight rules have evolved to address safe and efficient traffic flow and the challenges in evolving flight rules to address the increasing automation of flight operations. Second, airspace structure, where the paper addresses how airspace is structured to address current operations and how digitalisation and performance-based operations may influence future airspace organization. Third, infrastructure, where the paper looks at how the increasing automation of aerodromes and traffic management systems will drive safe interactions between all airspace users as well as the systems with which they will need to interoperate efficiently. Fourth, and last, the paper addresses considerations for technology maturity with considerations for the introduction of maturing technologies, including trade-offs between the automation level, operational risk, and robustness of these technologies. It should be noted that this paper recognizes that increasingly automated operations will also have an impact on approaches to aviation security, but does not make any recommendations within that domain.

This paper suggests some areas where recommendations to address the introduction of new and increasing automation into the airspace environment may be needed. The considerations in this paper are not intended to prescribe specific work or work priorities to existing JARUS work groups. The JARUS automation work group maintained an ongoing dialogue with existing work groups to harmonize the content of this paper with their existing and planned work insofar as practical. Decisions on future work motivated by the contents of this white paper are left to the respective JARUS work groups to propose and for the JARUS Plenary to approve.

1. Flight Rules

1.1 Introduction

Controlling traffic involves perceiving air traffic and making decisions to support the efficient flow of air traffic and ensure the safe separation of aircraft from other traffic or hazards. This is achieved by monitoring and directing aircraft movement, de-conflicting traffic, managing air-ground communication, providing real time information to operators and designated separators for decision-making, and activating contingency or emergency procedures when needed. The future airspace ecosystem will include a mix of aircraft that are piloted differently (conventionally crewed aircraft, single pilot, remote pilot, non-conventional pilot, no pilot), with varying levels of on-board and infrastructure automation. Aircraft performance and range will be different depending on a number of factors, including electrification and expanded use of alternative fuels, thus requiring changes to both Air Traffic Management (ATM) and aerodromes. Operation of new and emerging entrants will range from low altitude operations to high altitude platform systems, supersonic aircraft, and space vehicles.

With the anticipated increase in the number and diversity of airspace users, Air Traffic Control (ATC) will not be able to efficiently manage and support such a large scale of diverse traffic using current human-centric methodologies without resorting to prohibitive restrictions or requiring additional resources, both of which are not viable to support operations at scale. Airspace is a finite resource and therefore, segregation of different types of airspace users may be feasible in the short term, but is not scalable and will reduce the level of access and capacity to existing airspace users which is not desirable. However, as traffic numbers increase, integration will be needed if efficiency is to be maintained/achieved. As a result, there will be a shift from a human-centric construct (where automation is only supporting decisions) to a systems-centric construct (where automation will carry out routine tasks). At the same time, an operator may manage a fleet of remotely piloted aircraft instead of a single aircraft. This requires a re-visit of some of the underlying assumptions governing flight rules and how traffic is managed to ensure that operations remain safe and efficient with equitable access to airspace.

The airspace system as we know it needs to change to make it more accessible – particularly to new entrants, and scalable while still maintaining the safety of existing operations. The future airspace and traffic management system needs to be ready when the new types of aircraft are ready. However, the evolution to this end state will require parallel operation until automation on board and on ground are proven to be mature to replace the current environment. While segregation of new entrants may be needed to test out the technology as an interim step to gather the data and confidence necessary to prompt new regulation, over time operation of new and emerging airspace users will blend with other users without disrupting existing operations to the extent possible.

The primary purpose of existing flight rules is to ensure safe separation and navigation of aircraft to limit the risk to other airspace users and persons or property on the ground. Visual Flight Rules allow the greatest flexibility in flight trajectories by leveraging the direct coupling of the operating environment to the cognition of the human vehicle operator, through the pilot’s visual perception of the environment. These rules permit the trained pilot to safely navigate the aircraft and maintain adequate self-separation from other vehicles (as the designated separator), terrain and surface obstacles, in the visual field. Instrument Flight Rules allow access to the airspace in all weather conditions by leveraging instrumentation on the flight deck and on the ground, working cooperatively with other IFR traffic and air traffic control (as the designated separator) to impose structure and translate measurements of the environment to the cognitive process of multiple human actors in both domains. These rules assign clear accountability for safe operation and separation and permit the pilot to safely navigate the aircraft using onboard sensors and technologies in cooperation with the air traffic controller who uses radar and other instruments (including terrestrial systems) to provide sequencing, separation from airborne hazards, and other services to the pilot.

The existing rules consider a pilot being on-board an aircraft to manage separation or “see and avoid” other aircraft, obstacles, and terrain. The current rules do not allow alternate means of compliance (such as “detect and avoid”) nor provide a means to safely separate unmanned aircraft operating BVLOS via flight rule requirements. Some initial IFR operations of UAS may be enabled with waivers or new rules to allow operations without the use of a pilot on-board to visually navigate or separate from other aircraft. Future automation (in airborne and in ground systems) will change the roles and behaviour boundaries between pilot, controller, and the operator regarding who is the designated, accountable separator. Therefore, a highly automated airspace and operation will require a change or evolution of the existing flight rules. Towards this goal, consideration should be given to the concept of new flight rules to support increasingly automated aircraft (e.g., automated flight rules, AFR, digital flight rules, DFR), as a new operating regulation to augment but not replace VFR and IFR.

1.2 Regulatory Environment

The bulk of ICAO’s work on provisions related to new entrants has been focusing on non-passenger carrying RPA operating in an IFR environment. This does not reflect the long-term vision of various types of new entrants operating across borders, nor can IFR separation requirements be applied to low altitude, high density urban operations envisioned for small RPA delivery and other advanced air mobility concepts. As an outcome of the ICAO High Level COVID Conference, held in 2021, ICAO was requested by its member States to continue development of the UAS regulatory framework and integrate UAS in the Aviation System Block Upgrades (ASBU) framework under the Global Air Navigation Plan (GANP). During ICAO Assembly 41 many papers were presented by member States identifying challenges posed to future airspace operations (e.g., A41-WP/83, 177, 133, 236, 245, 360, 356, 599[1]). As an outcome of ICAO Assembly 41, ICAO was requested by its member States to develop a framework to support the development and regulation of advanced air mobility (AAM) operations and have subsequently stood up the AAM Study Group to look at these issues[2].

At the same time, regulators across different regions have started working on local requirements for new entrants. However, such operations are being addressed in isolation, and the constraints underpinning the existing system are imposed on new entrants, with little systematic considerations of their unique needs.

In the absence of global provisions for operations such as UAS parcel deliveries or AAM, there is

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[1] https://www.icao.int/Meetings/a41/Pages/WP_Num.aspx

[2] https://www.icao.int/safety/UA/Pages/Advanced-Air-Mobility-Study-Group-(AAM-SG).aspx

a risk of unharmonized approach which will affect manufacturers and operators. Considering that conventional aviation will have to share airspace with new entrants, and that some existing air operators are investing in the use of new entrants, it is important to move away from accommodation of new entrants to integration. Such integration must be supported by some level of global regulations to take advantage of digital information sharing and the potential use of automation to ensure safety, efficiency, and cost effectiveness. One of the challenges facing regulators is the availability of resources and expertise for oversight and certification, for lower altitude, high density operations and high-altitude operations.

1.3 Future Airspace Characteristics

The current airspace system possesses three fundamental weaknesses when it comes to new entrants: operators do not have current information about other airspace users, all information is located at air traffic control which means a clearance from a centralized source is needed for every change that an airspace user needs to make, and airspace classification is static and based on equipage and Air Traffic Service (ATS) provisions which limits access and does not support the development of new capabilities and system needs. In addition, the current airspace is at its capacity and often suffers delays and disruption from weather events and other unplanned circumstances.

In order to address the growing needs of the airspace users and not be limited by current operational practices, the airspace system needs to evolve. That evolution should include a shift from airspace users having limited data/information to having access to relevant information for safe and efficient mission execution, shifting from management by permission paradigm to management by exception, and shifting from static airspace classification to dynamic airspace adjustments based on demand, user equipage, and aircraft performance. Dynamic airspace may include airspace with performance-based requirements that can be met with ground-based support or on-board capabilities to allow operations by a diverse set of users. The evolution should focus on decentralized management by human-centric means to distributed, individualized management by the operator with assistance from automated systems.

1.3.1 Digital Information Sharing

Future aircraft capabilities will enable sharing of operational and aircraft performance information among airspace users and service providers before take-off and in real-time which will enable a determination of the performance classification. Operations will be enabled by sharing data and information, specifically with regards to location and operational intent based on the performance of the airspace users These digital locations and operational intents will be shared operator-to-operator, vehicle-to-vehicle, and/or operator-to-service provider, depending on the evolving technology maturity, evolving regulations, the type of operation, and functional capabilities enabled by equipment (on board and on the ground).

Digital information sharing and automation will enable a more coordinated approach towards traffic deconfliction and collision avoidance throughout all flight phases. At the same time, a high percentage of new and emerging operators are expected to have the capability to strategically manage their operation through interactive planning and orchestration of operational intent information. Digital access to airspace constraints can enable strategic de-confliction for multiple aircraft and demand capacity balancing. Weather provided by service providers will support mission planning, but may not appropriately support the safety of all flight regimes due to latency/precision of the data transferred. To enable airspace management in high-performance environments, real-time wind and temperature information coming from on-board aircraft equipment, would be required throughout a flight.

At low altitudes, the operator will be responsible for managing its operations safely within known constraints, without receiving regular instructions from ATC or UTM. Within that context, operators will be expected to continuously share and update their flight intent with each other or with the Unmanned Traffic Management Service Provider (USP), where available, to ensure traffic de-confliction and safe separation of trajectories. Automated decisions will be possible throughout all flight phases such that operators with the required capabilities and performance will be able to self-manage their operations and their interactions with other airspace users.

Where available, the USP is expected to have the capability to provide real-time information regarding airspace constraints and other aircraft intentions to UA operators and other traditional airspace users. A USP can support operation planning, intent sharing, aircraft de-confliction, conformance monitoring, and other traffic management functions. Capabilities akin to SWIM should be able to support information sharing between airspace users of heterogenous on-board capabilities and automation. NASA has also proposed many capabilities that build on the concepts of UTM in their recent reports on Digital Flight Rules[3]. NASA's proposed Digital Flight Rules are easier to implement in airspace that avoids legacy traffic flows through selective application in defined airspace.

The known level of confidence regarding adherence of the aircraft to the operator's shared flight intent may vary significantly between different types of aircraft due to the unique characteristics, equipage, and performance of each specific aircraft. Future systems will have the capability to capture and analyze data received from operating aircraft and provide probabilistic intents or predictions that contain the actual/flown path. Digital information sharing, through standardized protocols, will enable cooperative airspace and traffic management, as information about airspace users and other constraints will be available to all operators.

1.3.2 Management by Exception

An end state of autonomous aircraft and systems can be realized subject to specific conditions and requirements. An intermediate progression in on-board and ground automation will allow humans to evolve to system supervisors and make strategic decisions about system operation, leaving situations that require rapid response and alertness largely to automation. Future automation is expected to bring the humans attention to issues/events that cannot be resolved automatically and will require intervention. The extent of automation of functions and tasks to enable these capabilities will have an impact on the training and expertise required by operators to diagnose complex problems in this highly automated system.

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[3] NASA/TM–20205008308: https://ntrs.nasa.gov/api/citations/20205008308/downloads/NASA-TM-20205008308%20updated.pdf, NASA/TM–20210025961: https://ntrs.nasa.gov/api/citations/20210025961/downloads/NASA-TM-20210025961.pdf, & NASA/TM–20220013225: https://ntrs.nasa.gov/api/citations/20220013225/downloads/NASA-TM-20220013225.pdf

1.3.3 Alternative Classification of Airspace - demand & performance-based operations

The current organization of the airspace in classes was tailored at supporting a static description of the airspace, where each airspace class corresponds to a level of service. In a highly automated end state, aircraft are assessed and operated according to their equipage and performance characteristics, and therefore, classification according to specific available services and required equipage may no longer be needed. A more dynamic and flexible use of the airspace can be implemented when services are developed to support operational needs (e.g., spacing efficiency) rather than classifying based on available services. It is also possible within an existing airspace class to allocate a sub-part or a designated part of the airspace to a given operation or set of operations pending certain performance and cooperation rules being met.

1.3.4 Roles, Responsibilities, Behaviours and Expectations

With the future automation, aircraft capabilities and the characteristics mentioned in previous sections, the role of ATC and operators are expected to evolve. This evolution is likely to occur in increments with an increasing number of system users in an increasing volume of airspace able to leverage automation to interact more safely and efficiently at each successive increment. Technology, digitization, and data will provide new opportunities for improved system performance, less ATCO and operator workload, and enhanced human-system partnership for safety and efficiency. The pace of this evolution will be governed by regulator, ANSP, operator, and customer acceptance of evidence that automation can safely address sequencing and separation roles between potentially diverse airspace users in increasingly dense airspace.

Role of ATC

The role of ATC is expected to continue to grow into managing and enabling traffic and intervening in off-nominal situations, rather than what is predominantly done today in controlled airspace where the controller performs most of the designated separator tasks and holds the liability to manage traffic safely by clearance and direct interaction. Within that context, the role of ATC will shift to critical tasks, supervising the airspace and intervening in off nominal situations. The air traffic controller role will include managing trade-offs when human intervention is needed, which implies the need for extensive evaluation of human-machine teaming for normal and off nominal situations.

Role of the operator

The role of the operator will evolve to focus on configuring the system, managing trade-offs, setting priorities, managing risk and handling system constraints, as well as exceptions. The role of the operator may evolve to the role of designated separator for non-VFR operations in some airspaces, with the expectation each operator will be accountable to integrate with other traffic according to applicable operation procedures and new operating rules. Although operators will have accountability for safe separation, there may still be a safety monitor role for ATC to support airspace management (e.g., in the event of contingencies, or emergencies) somewhat analogous to current operations where separation services between IFR and VFR aircraft are not provided (e.g., some Class E airspaces). Clear steps (or procedures) should be defined to clearly identify the separation responsibilities for ATC and Operator, in each phase of the flight, such that a single responsible actor is ensuring separation.

Among other functions, the operator will supervise the operation of its fleet and where necessary investigate off-nominals that cannot be resolved by automation and take necessary actions. Future automation will have the capability to handle large quantities of data and provide the operator with what is needed for them to operate their aircraft safely and efficiently during nominal or off-nominal conditions. Automation will also have the capability to generate alerts about exceptions that cannot be handled automatically.

Shared responsibility for safety

The key paradigm shift for future operations, will lie in the degree of authority over the trajectory and shared responsibility for safe separation. Management by exception like in the Trajectory Based Operations (TBO) concept, will be the norm and intervention the exception. Traffic density and complexity will dictate how separation is provided.

1.4 Flight Rules for Future Operations

1.4.1 Flight Rules and New Entrants

Flight rules are about where the operator is going to fly and how, what the operator is responsible for, what equipment is required, what performance levels must be met, and what services and support infrastructure is required to achieve operational safety and efficiency.

With digital information shared air-air or ground-air and future automation, some human cognitive processes involved in safe separation and navigation will be replaced with digital processes. Future operations will be characterized by cooperative separation or community-based separation, whereby operators are able to separate their aircraft from other traffic and obstacles using ground and on-board automation. In such an environment, the operator and ATM system have a shared responsibility for safety and there is a coordinated flight and flow decision-making by operators and with applicable UTM/ATM providing greater flexibility and making the best use of available airspace capacity. Operators will be able to take on increasing separation responsibility and trajectory management authority. The ATM system will simultaneously shift from being the separator of aircraft to providing limited safety oversight under well-defined contingencies. Operators will be responsible for managing their operations safely within known constraints (e.g., performance requirements, available trajectories), without receiving ATC voice instructions. In future operational environments, ATC will not be the sole source of airspace operational information and elements of separation management will be with the operator.

In such an operational environment, the operator will have a digital view of the operational environment (including constraints, obstacles, and other aircraft) as well as weather information (ahead of the mission and real-time during flight). In that context, an additional flight rule which can provide VFR-like flexibility with IFR-like access, in all-visibility and weather conditions, will enable operations of new entrants to scale. This additional (or new) flight rule is envisioned to be a digitized version of VFR. If in the future there is a tipping point with a critical mass of operators who have the capability to operate under the additional (or new) flight rule, then the digitized version of VFR may replace VFR operations in that airspace. For the purpose of this section, the additional (or new) flight rule (the digitized version of VFR) will be referred to as Enhanced Flight Rules (EFR).

Currently, most States require VLOS unmanned aircraft to yield right of way to all other aircraft. As automation evolves, there will be a need to consider whether right of way will still be applicable in a collaborative airspace management environment. Performance will play a role in that context, for example, speed and manoeuvrability, as well as ability to see, be seen, detect and be detected.

The additional (or new) flight rule (EFR) should enable operations in shared airspace, irrespective of the type of operation, as long as the minimum requirements to operate under the flight rule are met. Segregation of operations under EFR may be used during the early stages of implementation. During the transition to an "end-state" where all operations are conducted under EFR, there might be new obligations added for aircraft needing to operate in the same airspace as EFR aircraft (e.g., electronic conspicuity and connection to UTM, remote identification, and publication of intent and flight data). Also, during the transition phase, EFR operations in some airspace may be required to have equipage that allows them to safely integrate with legacy users of that airspace.

1.4.2 Implementation

A starting proposal for EFR, once drafted by the regulatory community and industry, can be communicated to ICAO for further analysis and assessment (e.g., in support of the ICAO AAM SG). The details included in this section provide a baseline for such a proposal and highlight some of the key assumptions and considerations that need to be taken into account. Given the process requirements to arrive at a global consensus with regards to EFR, work should continue to support current and near-term operations under existing flight rules. Several issues need to be considered in the proposal for EFR, including:

1. Performance Requirements
2. Responsibilities
3. Weather conditions
4. Cyber Resilience
5. Interface between UTM and ATM
6. Applicable Technical Specifications
7. Data governance for information sharing
8. Human training

In order to ensure safety and to verify the performance of a new system and new type of flight regime, parallel implementation can be used in a specific airspace volume or region. This will enable analysis of the diagnosis and decisions made by the controllers compared to the new system/automation and fine tuning the system as needed. Such parallel operation can be used by regulators as an operational validation phase to oversee how the automation and systems can interact with real-time traffic and what outputs are provided to controllers. Parallel operations will also enable the comparison of system output error against acceptable error margin. After resolving system errors, phased deployment of new or simplified flight rules can be used, whereby the new type of flight regime can incrementally replace the older regime, where needed.

Dynamic/flexible corridors that adapt to the type of operation and enable separation from conventional aircraft is one approach that can be used. The variability of these corridors may be limited in terminal areas, especially for initial uses in Class B/C (and perhaps even Class D) airspace. The status of such an airspace volume or corridor will vary over time, enabling it to be available dependent upon environmental conditions (e.g., wind, weather), traffic density/demand, and airport configurations. A dynamic and flexible use of the airspace will be used, building upon the flexible use of airspace mode of operations, with the whole process managed by automation. In this construct inside an existing airspace class a sub-part or a designated part of the airspace might be temporarily allocated to a given operation or set of operations pending certain performance and cooperation rules being met.

1.4.3 Air/Ground Capabilities

Automated detect-and-avoid capabilities and other onboard contingency management capabilities will be needed to handle situations where communications are lost without the need for human intervention. There should also be contingency capabilities and procedures for when human intervention may be required but would not be possible due to the necessity for rapid decision-making (though these situations should be well understood, and contingency behaviour well described). Events that cannot be resolved by automation will still require human intervention, however that responsibility is expected to reside with the operator, leveraging aircraft technology and sensors. One key aircraft component will be one or more common elements of electronic conspicuity to allow aircraft to cooperate in maintaining safe separation. As a last layer of defence and for traffic collision avoidance with unplanned/unpredictable traffic, the aircraft will need to have automated obstacle and collision avoidance. When flight re-planning occurs after departure, tactical deconfliction should address uncertainty and changing operational conditions.

The types of aircraft (manned and unmanned) sharing airspace will vary in terms of on-board automation, performance, and capabilities. Aircraft and ground system performance requirements will be required to drive the type of technology needed to meet the performance requirements. Digital sharing of data and information, specifically with regards to location and intent, will be required for the safe operation of all types of operators. Within that context, several issues will need to be addressed such as integrity and latency.

At the same time, with future innovations in CNS technology and advancements in technology and data sharing capabilities, the assumption that separation services must primarily be provided externally to the aircraft can be challenged. At lower altitudes, the UTM service providers will have the capability to provide real-time information regarding airspace constraints and other aircraft intentions to UA operators. For RPA IFR operations, the RPA will be required to provide ATC with identification, intent, and telemetry information over an information exchange link. It is expected that in the future there may be a convergence point between ATM and UTM providing an integrated approach to air navigation services that meet the requirements for all types of airspace users.

Strategic de-confliction and dynamic airspace allocation will allow operations to take place without the need for regular operator and ATC intervention, as it is the case today. The underlying principle for dynamic airspace allocation is that the aircraft which utilize it will be equipped with the required automation technologies. The boundaries of dynamic airspace allocated for such purposes will be digitally available. Access to and from the allocated dynamic airspace is expected to be automatically coordinated and be subject to a digital authorization. Conventional aircraft operators may choose to equip with technology to enable smooth integration into the allocated dynamic airspace, and when operationally necessary. As more aircraft are equipped with technologies that meet the performance required for operation in such corridors or airspace volumes, there may be a tipping point where a majority of the airspace users can fly under the new procedures and new type of flight regimes. The tipping point needs to be agreed with all airspace users.

2. Airspace Structure

2.1 Introduction

Current airspace classification is characterized by the type of services provided (ATCS, FIS, ADS, ALS[4]) and by the type of flight rules (IFR, VFR[5]). As highlighted in the Flight Rules section, such classification has some issues in accommodating UAS operations in VLL or High Altitude Operations (HAO) due to the intrinsic characteristics of both the environment and the craft involved. Furthermore, as it might be the case for HAO in some States, the new traffic might operate at a level where the airspace has no classification.

Digitalisation and Performance Based Approach are two of the pillars of future aviation. Automation is an essential part of both concepts, and it is important to understand how and where levels of automation can contribute to establishing the new airspace framework with the aim of reducing to minimum the airspace segregation. There will be a shift from the current human-centric construct (automation level 0-3[6]) to a systems-centric construct (automation level 4 and 5). To enhance the performance of the entire system, regardless of the service provided, it is important that the level of automation of airspace users is compatible with the level of automation allowed in the airspace.

At the same time, especially for high levels of automation, the distinct role air traffic controllers and pilots have today might start to be less rigidly defined and more fluid when considering conflict management. As noted previously one or more common elements of electronic conspicuity will allow all aircraft to cooperate in maintaining safe separation, and also allow ground systems to provide safety support. The interactions between automated systems on aircraft and automated conflict management systems provide for a wide range of implementation possibilities, and while clarity on the responsibilities of each flight and for each airspace manager for maintaining the safety of the airspace must be clear to all airspace users, where the responsibility lies at any given moment may shift depending on the active capabilities of the aircraft being managed.

2.2 Regulatory Environment

ICAO Annex 11, Air Traffic Services, details the general scope of Air Traffic Services as well as the aim of each service. Some of these objectives might be reviewed under the light of UAS because the absence of pilot/passengers on board, together with the risk based UAS operation classification (Category A, B, & C[7]), could make some of the current ATS services unnecessary or not applicable to UAS.

Regardless of this different approach, some components are essential and cross-cutting in all possible ATM/UTM structures. These aspects can be derived and adapted from ICAO DOC 9854

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[4] ICAO Annex 11 Air Traffic Services

[5] ICAO Annex 2 Rules of the Air

[6] JAR_doc_21: JARUS Methodology for Evaluation of Automation on UAS Operations: http://jarus-rpas.org/wp-content/uploads/2023/06/jar_21_doc_JARUS_Methodology_for_Evaluation_of_Automation_for_UAS_Operations.pdf

[7] JAR_doc_9: JARUS UAS Operational Categorization: http://jarus-rpas.org/wp-content/uploads/2023/06/jar_10_doc_UAS_Operational_Cat.pdf

Global Air Traffic Management Operational Concept that reports Airspace organization and management (AOM), Demand/capacity balancing (DCB), Aerodrome operations (AO), Traffic synchronization (TS), Conflict management (CM), Airspace user operations (AUO), ATM service delivery management (ATM SDM).

Considering both manned and unmanned aircraft, with such different capabilities and performances, there is the need of flexible, scalable, and reliable traffic management systems that can accommodate all the requests. Such a system should be designed generally to accommodate all types of aircraft and may contain varying types of automation on-board and on-ground. This advanced air traffic management system would also need to bridge communications between aircraft operating in airspace which are managed through traditional ATM and those managed with new systems and services such as UTM and high-altitude operations. The predictability of flight characteristics and conditions, from preferred trajectories to weather data, are the basic computation elements from which all systems can interact to accommodate all the demands. For example, Trajectory Based Operations are an option to start considering the conflict management issue. This concept is highly interconnected with the information exchange and with the possibility to automatically process information received to ensure compliance with the agreed trajectories. These capabilities can also be paired with the airspace user level of automation and, consequently, airspace classification has to consider this aspect as well.

Another point to define is the classification of the traffic: if the aircraft is provided with services to prevent collision with other aircraft (Conflict Management Service), the flight should be considered managed. If the conflict management service is not provided, because of the capabilities of the aircraft or of the pilot, or due to the nature of the operations the traffic is unmanaged.

Managed traffic shall be under the direction of only one unambiguously identifiable separator at any given time (which may be a combination of human and automated systems). If operators of individual aircraft or groups of aircraft are the single separator with respect to other aircraft in their airspace, then they can only share an equal separation responsibility with other operators if both operators have the same information and agree to a harmonized use of this information to exercise their conflict management responsibilities. Service providers can assist operators in the sharing of information and in communicating changes to flight trajectories (i.e., operational intent) to other operators. In this division of roles, it is important for all parties to understand who is responsible for separation provision intervention capability (i.e., the ability to detect and solve a conflict) which can vary depending on whether intervention is from a human or an automated system. In all cases, the safety of the airspace will be enhanced by interoperable collision avoidance systems in each respective aircraft to address any failures of the separation provision.

2.3 Automation Level Group ALG

Automation is the key point to enable all the considerations above, while performance expectations will be set independent of automation capabilities, it is envisaged that high levels of performance will only be achievable with a high degree of automation. JARUS classifies the automation into 6 levels (0 to 5). To construct a safe airspace structure and avoid a proliferation of classes and sub-classes increasing the overall complexity, it is necessary to group levels with similar characteristics. In section (JARUS Doc 21 Figure 1, Table 1) of the document, several characteristics are listed and allocated in the different levels. To ease the possibility to identify which part of the human-machine (or fully autonomous) system oversees the actions, and so to identify the subject whom responsibilities are put upon, cognitive capacity and authority to make

decision are identified as the most relevant items.
According to these parameters, three automation level groups (ALG) have been identified:

Legacy (L): Functions required to safely integrate into the airspace (e.g., remain well clear, communicate trajectory, manage trajectory) are automated at or between levels 0 and 2 with the associated level of human oversight.

Machine-aided (M): Functions required to safely integrate into the airspace (e.g., remain well clear, communicate trajectory, manage trajectory) are automated at levels 3 or 4 with the associated level of human oversight.

Automated (A): All functions required to safely integrate into the airspace (e.g., remain well clear, communicate trajectory, manage trajectory) are automated at level 5 with clearly defined human responsibilities over the management of system level tasks.

2.4 Future Airspace Characteristics

To support safe interoperation of aircraft the airspace structure should take into consideration the nature of the operation (predictable or unpredictable) compared to the type of traffic (managed or unmanaged) and the level of automation (of the airspace/services or of the airspace users).

2.4.1 Considerations for Traffic Environment

The traffic environment of the airspace is fundamental to the management concepts being implemented. Specifically, the difference between known traffic environment and an unknown traffic environment. In a known traffic environment all aircraft are cooperative and the air traffic management system (as well as other airspace users) retain awareness of aircraft operating in the air space at all times. In an unknown traffic environment the aircraft may not providing active updates on aircraft position to ATM or other airspace users. The traffic environment is an important aspect as known traffic is required for humans to provide separation and other ATM services (as services cannot be provided to aircraft which are not communicating with the ATM system). As services are developed and deployed the environment should become more known (e.g., in the UTM/U-space construct). An example of this is the: CORUS Airspace classification (X, Y, Za, Zu)[8] for service roll-out.

2.4.2 Considerations for the Conflict Management Environment

Clear communication of available services to airspace users is key to safe operational planning. The type and nature of the conflict management environment is a major defining factor in how airspace safety is assured, and as a result must be available to all operators ahead of mission planning. Airspaces where services are not provided or airspaces where services outage are occurring need to be readily available and easy to understand.

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[8] https://www.sesarju.eu/node/3411

2.4.3 Considerations for Segregated Environments

While technology develops and ATM services begin rolling out it is expected that air traffic may be segregated (e.g., by equipment, automation level, or aircraft type) to evaluate system performances and provide predictable managed traffic. When evaluating segregated environments the major concern is ensuring that the segregation methodology (e.g., boundaries of an airspace corridor) is clearly delineated and respected during all parts of the operation. Technology or procedures which are used to support segregated environments (e.g., Geo-fencing, minimum navigation performance) need to be well described and contingencies understood to avoid creating additional hazards to aviation safety when operating in these environments.

2.4.4 Considerations for Interim Solutions

Redesigning airspace is an effort that should not be taken lightly. Traditionally, airspace classifications supporting day-to-day operations in an airspace have been developed over years. While it is important to understand and accommodate for disruptive technology to enable new and more efficient operations, consideration needs to be given when blending these operations with traditional systems. Evolutionary advancements in airspace designation or ATM service delivery provide an opportunity for changes to be incremental (e.g., addition of a new service) and targeted (e.g., cooperative tracking) to address specific emerging risks in operational airspaces. Alternatively, expansionary advancements in these same areas could provide for more modular operations (e.g., identifying temporally restricted airspace) and give a basis to ensure safety risks are addressed holistically by all operators. No matter the method of development, the goal of these solutions should be to develop performance expectations as well as service definitions/limitations for the envisioned end-state of the airspace.

2.4.5 Considerations for Controlled Airspace

Inside the controlled airspace, Conflict Management Services (CMS) provide separation to all traffic. Only traffic which can interoperate predictably with these services (e.g., in accordance with defined flight rules) can integrate into it. Interoperation with these services requires operators to know to what degree the services may be automated, and to what degree their operations may need to be automated to support safe and efficient operation. To this end each ALG (See Section 2.3) can be appended to an existing airspace class (e.g., Controlled Legacy (CL), Controlled Machine-aided (CM), Controlled Automated (CA)). Particular care should be taken in ensuring the interoperability of aircraft equipment and operational infrastructure when blending automation environments (e.g., level 4 system wanting to operate in the CL airspace class).

2.4.6 Considerations for Uncontrolled Airspace

Both predictable and unpredictable traffic can operate into uncontrolled airspace. CMS may not be provided in this airspace (though there may be cases, such as operations at very low altitudes away from airports, where the airspace is uncontrolled but has a cooperative CMS provision). Safety of the operations is charged to operators and pilots. While at the start of roll-outs only systems which comply with Legacy expectations may be permitted operation in the UL airspace class, as systems evolve and capabilities are improved some Machine-aided systems can be permitted operations as well.

2.5 Services

Services will be provided to achieve ATM objectives and these objectives should be independent from the level of automation of the airspace or of the users. Consequently, the service is unique, but the deployment of the service varies in accordance with the level of automation.
For example, the Conflict Management Service has the objective to limit, to an acceptable level, the risk of collision between aircraft and hazards. This objective can be achieved using different level of automation according to service provider and user characteristics.
Considering ALG, aircraft from different groups operating in the same airspace will have access to the same services (provided in accordance with the airspace designation), but the delivery mechanism for these services will change to fit the higher/lower (or various) level of automation of the group. For example, the L group will have conflict management service (CMS) in a way very similar to the current ATC because of the limited interaction the two systems (ATM-aircraft/pilot) can have, whereas operations equipped to interoperate with Machine-aided services, the ground CMS would interact directly with the airborne systems.

To address the issue of interconnectivity and possible changes of level of automation during the flight, systems and procedures are required to monitor and react to changes in the automated capability of services and aircraft. For example, is a Level 3 equipped system able to operate in CL (identified for level 0-2)? Does it have to “downgrade” its capabilities or do the required CM capabilities include provisions for interoperation with CL?

On the opposite side, there are the airspace performance requirements: CL, CM, CA could allow for different degrees of CNS performance to support separation. The approach adopted for C2 Link in RPAS (RLP, QoSR, SLA) provides a baseline for evaluating how these services may interact to support separation. Service performance requirements might also be derived out of a system theoretic process analysis of the automated airspace environment.

2.6 Separator

Clarity on who is responsible for maintaining separation of aircraft in a particular airspace will continue to be crucial in automated operations. In the ICAO Concept, “the ATM system will minimize restrictions on user operations; therefore, the predetermined separator will be the airspace user, unless safety or ATM system design requires a separation provision service”[9]. If the ATM system determines either for safety or design that a separation provision service is needed (e.g., increased density of aircraft operations), then it does not mean that the airspace user can become the separator simply on request. In the first case (safety), it has already been determined that the airspace user is not an appropriate separator on safety grounds. In the second

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[9] ICAO Doc 9854 Global Air Traffic Management Operational Concept

case (design) it has been considered for reasons of ATM performance that the airspace user is not the best separator. This is not to say that there are no cases where the delegation of separation to the airspace user is possible, for clearly that is allowed for in the types of separation provision and in delegation of separation – however it would have to be part of the second case and be part the ATM system design (that is procedures defined for when it will occur).

In the ICAO Concept, “the role of separator may be delegated, but such delegations will be temporary”[9]. There are requirements for delegation in the ICAO Concept. It is important to note that it is not reasonable to assume that separation can be “handed back” before the termination condition. It may be possible, subject to negotiation, but it is not guaranteed. An acceptance of the delegation is also an acceptance of the whole period of the delegation.

In the ICAO Concept, “in the development of separation modes, separation provision intervention capability must be considered.”[9]

The separator can be the airspace user, a service provider or automation. “Separation provision intervention capability refers to the quality of humans and/or systems to detect and solve a conflict and to implement and monitor the solution.”[10] The intent is that the best separator for a given situation is chosen.

3. Infrastructure

Enabling scaled automated aviation operations requires significant considerations related to the supporting aviation infrastructure. Traditional aviation operations depend on many diverse pieces of infrastructure to support the aviate, navigate, communicate, and integrate tasks. Examples include weather stations, instrument landing systems (ILS), radio navigation aids (VOR, NDB), global navigation satellite systems (GPS, Galileo), ground or satellite-based augmentation systems (EGNOS, WAAS), ground radio stations (VHF, HF), surveillance stations (RADAR, Mode C, Space-Based ADS-B), telecommunications, and datalinks (CPDLC). In many jurisdictions this infrastructure is centralized at aerodromes and in air traffic management systems.

The different capabilities that exist in a particular operational area need to be well coordinated to aid in flight & contingency planning – there is a need to have common understanding of the available infrastructure, services, and operational limitations to support domestic and international operations.

Infrastructure will be the driving consideration when evaluating equipage requirements for aircraft in specific operational areas. Aircraft will need to have the infrastructure required to permit safe operations (e.g., CAT III ILS required for automated precision landing). Infrastructure providers need to provide timely updates to operators on outages or limitations (e.g., GPS RAIM or closed portions of movement area, enroute charging station status) so operators can modify their operations (e.g., information to support demand and capacity balancing).

Civil aviation authorities, air navigation service providers, and industry partners may need to leverage the increased connectivity and flexibility available through a cloud service infrastructure to support highly automated operations like UTM at scale. This flexible and scalable infrastructure can support a range of connectivity between stakeholders, including airspace authorizations, flight approvals, airspace activity notifications and the collaborative sharing of flight intent and other flight information between operators, airspace regulators, service providers and other stakeholders. Infrastructure information sharing needs to address requests for status updates from the UTM operators, or aircraft, and assure requests have been satisfied.

Infrastructure updates have long timelines and require significant investment and typically involve complex municipal, regional, and national coordination. These plans are further complicated by the need for common understanding at the international level. ICAO serves as the central point for international standardization on aviation infrastructure including aerodrome and ATM operations.

With respect to authorization of infrastructure, the risk-based approach developed in the JARUS UAS Operational Categorization[10] still holds. When considering approving operations of these systems organizations should include the risk factors and specific mitigations required to support safe operations.

3.1 Aerodrome Operations

Many commercial UAS operate without the need for fixed infrastructure required for traditional aviation. While these systems are typically quite capable, they are usually limited to Category A operations. As operators look to scale-up, fixed infrastructure provides an opportunity to expand flight operations. This infrastructure may range from small launch/landing pads (e.g., vertiplaces[12]) for Category A & B operations, to large traditional airports or heliports (e.g., vertihubs[12]) for Category B and C operations. These different types of aerodrome-like infrastructure may be

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[10] JAR-doc-9: http://jarus-rpas.org/wp-content/uploads/2023/06/jar_10_doc_UAS_Operational_Cat.pdf

required to enable certain operations, and to fully support automated operations the aerodrome requirements need to be understood.

Capabilities are needed to support both automated flight as well as automated facility management. This document only considers the concepts required for automated flight as facility management requirements will vary from one operator and deployment to another (there have been some efforts to identify expectations for common use infrastructure[11]). The key aspects to enable automated flight operations are related to critical phases of flight: taxi, take-off, and landing. For these phases of flight the interactions between the available communication, navigation, surveillance, and sequencing (i.e., demand/capacity balancing) systems at the aerodrome and the communication, navigation, and aircraft management systems on the aircraft need to be well understood (e.g., NASA Small Aircraft Transportation System Higher Volume Operations concept[12]).

UAS operations challenge the traditional separation between ground systems and aircraft systems. Operations into aerodromes will continue to challenge that paradigm but offer opportunities for increased safety and resiliency by allowing for capabilities to be distributed both on-board and on-ground. The safety case for operating a particular automated aircraft into an aerodrome will depend on the functional architecture of the aircraft systems as well as the interaction with the ground systems (e.g., ground-based detection of UAS or other aircraft). As different capabilities are realized on the ground side the requirements for equipment on the aircraft to interact with these systems will need to be clearly identified ahead of authorizing aircraft operations with the infrastructure.

Operations at certified aerodromes are currently being studied by the ICAO Aerodrome Design and Operations Panel along with the ICAO RPAS Panel. The panels are working together to determine design requirements and operational principles for operations of type certified RPAS in certified aerodrome environments. Additional work has been done by some CAAs including the FAA (Engineering Brief 105-Vertiports[13]) and EASA (Prototype Vertiport Design Specification[14]) providing a starting point for considering the technical design of aerodromes and how automation may impact the standard. These standards need to consider unique hazards from new entrants that need to be managed as well as associated safety management considerations. The certification status of aerodromes and any associated safety considerations for non-certified aerodromes need to be shared with users.

3.2 Traffic Management Systems

Traffic management systems provide the bulk of ground-based infrastructure in traditional aviation. As automation challenges these legacy systems there also arises the opportunity to modernize new ATM infrastructure in support of scaled automated operations. Many of these systems will support operations in airspace where automated approval and management of some operations is permitted (e.g., UTM, U-Space) in accordance with community operating principles, but the strain on traditional ATC systems is already being felt. Some automation is already deployed in ATC systems (e.g., decision aids, filtering, tracking and alerting in surveillance systems) and it is expected that this will continue to serve both safety and efficiency of air traffic management.

To adequately serve all airspace users infrastructure needed to support airspace management of

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[11] https://ntrs.nasa.gov/api/citations/20210010603/downloads/20210010603_MJohnson_VertiportAtmtnConOpsRprt_final.pdf

[12] https://ntrs.nasa.gov/api/citations/20050217426/downloads/20050217426.pdf

[13] https://www.faa.gov/sites/faa.gov/files/2022-09/eb-105-vertiports.pdf

[14] https://www.easa.europa.eu/en/downloads/136259/en

automated operations may include ground, air, and and space-based components operating in interconnected networks. These components serve the traditional communication, navigation, and surveillance activities of ATM, but their operation will rely more on automated systems and in some cases autonomous decision-making to support continued safe flight. Cyberspace cloud infrastructure may also be useful to support collaborative sharing of flight approvals, flight intents, and airspace constraints to stakeholders across disparate domains.

A number of technologies are in development to augment the existing CNS infrastructure and will need to be matured to support all categories of automated aircraft operation. These include precision landing systems, resilient position/navigation/timing solutions, diverse surveillance systems, and reliable communications systems and data links. The path to maturity of this technology follows similar patterns to aircraft technology moving from low-risk operational environments to higher-risk as the technological capability and reliability is demonstrated over time.

3.3 Considerations for Infrastructure Design

As a result of the long lead time in planning and building infrastructure, the requirements for the design need to be understood well ahead of deploying scaled operations. In the traditional aviation operating environments the inclusion of automated systems can be well understood through the existing procedures and technologies used to manage operations. For future aviation operations (e.g., AAM, High-Altitude Operations) these procedures are not well understood, and many rely on the automation of various capabilities to achieve operational goals (e.g., improved airspace efficiency, clear management of safety margins). Consequently the design of the automated infrastructure will impact the scope and limitations of where certain operations may be approved.

While there are many possible configurations for the deployment of infrastructure, there are many similarities between future cooperative airspace concepts and recent research into diverse, unstructured, and communications challenged environments. The United State Defense Advanced Research Projects Agency Subterranean challenge [15] established operational experience of autonomous, heterogeneous systems operating in this type of environment. The autonomy framework that teams developed[16] to achieve resilient performance of the system interactions in these conditions established principles that can be applied to operational architectures for a reliable coordinated network of airborne autonomous systems. These principles are summarized below.

3.3.1 Modularity by Design

Designing for modularity enables the operational ecosystem to handle variability in both subjugate implementations and overall operational expansion/scaling:

Operational Ecosystem perspective

- The ecosystem is able to accommodate a variety of Actor/Agent/Vehicle performance levels without having an effect on the overall aggregated performance;
- Modular capabilities (e.g., PNT systems) and authority for their management can be aggregated into ecosystem actors (e.g., Provider of Services for UAM (PSU)) as operations and policies mature; and

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[15] https://www.darpa.mil/program/darpa-subterranean-challenge

[16] https://arxiv.org/pdf/2103.11470.pdf

- Impacts of changes to the ecosystem (e.g., Security discoveries) can be isolated and managed at the module level.

Operator perspective
- Autonomous behaviours introduced and matured incrementally;
- Integration and implementation of heterogeneous sensors enabling autonomy through increased understanding of the environment semantically and informing the network;
- Continued safe flight and outcomes under conditions of degraded health in variable environmental conditions through layered contingencies;
- Assistive capabilities supporting workload reduction in consideration of human engineering requirements;
- Situational awareness capture and dissemination including transparency of the autonomous intentions to the pilot-in-command (PIC); and
- Redundant and independent communication links for all phases of flight and areas of possible operation.

Regulatory perspective
- The promulgation of standards and regulations for ecosystem capabilities in support of safe and efficient operations (e.g., Surveillance) can be developed more efficiently by bounding the scope of consideration in their rulemaking; and
- Operational infrastructure implementations are able to be defined, configured, operated, and managed as independent functionality. This supports the risk-based oversight by civil authorities to support the resilience of safety critical functionality.

3.3.2 Uncertainty-Aware Architecture

The design of the airspace system management architecture has to recognize that there will be some degree of uncertainty among the data that is being shared (or not) and enables the integration of diverse systems of varying performance levels into an operational space. Management of uncertainty needs to be carefully considered when looking at infrastructure requirements and design criteria.

1. Autonomy architectures should be robust to unmodeled uncertainties in both airborne and infrastructure solutions which includes:
    - Incorporation of multi-modal sensors (e.g., LiDAR, RaDAR, EO, IR), means to detect sensor failures and implement mitigation strategies;
    - Loose coupling between sensors where consensus is being determined across sensor modalities to detect anomalies;
    - Tight coupling where sensors are operating within clearly specified opearating parameters; and
    - Plan to Manage (e.g., Sense, Infer, Act).

2. A Common Operating Picture (COP) provides the necessary baseline to manage all operations within a particular infrastructure service area and should include:
    - The network actor responsible for the COP needs to have information on degraded performance of network actors to maintain accuracy of the COP;

- Computational resources in the active network should be distributed to improve scalability and reduce communication bandwidth;
- Augmenting geometric information with semantics can increase the resiliency of the COP; and
- Repeated sensor collections along routes from a variety of heterogeneous systems will improve COP resilience.

3. Strategic Planning supports early identification of hazards/risks and adjustments to changes during the execution of the operation:
   - Awareness of uncertainty plays a critical role in performance of the operators as a cohesive network;
   - Balancing scalability with information fidelity; and
   - Consistency of strategic plans vs resiliency to tactical changes in COP.

4. Bandwidth-aware communication system designs to ensure service to those operating within the service area, and limit operations when bandwidth approaches safety limits.
   - Considerations for loss, routing, quality of service, and security; and
   - Predictions for available link bandwidth in mission planning.

4. Technology Maturity

4.1 Introduction

Many technologies are needed in order to drive increased automation of aircraft and infrastructure systems. These technologies can vary wildly in their scope, design, and pedigree with many proponents of future systems looking to leverage machine learning applications along with traditional systems. While the regulatory approaches for approving these technologies is still evolving (e.g., EASA Roadmap for Artificial Intelligence[17], Machine Learning Application Approval[18], Usable guidance for Level 1 Machine Learning[19]). As a consequence, determining which technologies are appropriate to consider for integration into a future airspace management system need to be carefully considered. Determining when a particular technology or solution is "mature" enough (e.g., has sufficient characterization of capability, documented limitations, and trustworthiness) for a particular operation requires a number of different considerations to be taken into account. This section outlines considerations for the development and acceptance of technology in an increasingly automated operational environment.

4.2 Problem Dimensions

As new automated capabilities are envisioned, developed, and deployed the technology which enables those capabilities will mature from an initial experimental state through to matured in-service systems. Ensuring that automated technologies are being applied in operations with the appropriate level of safety assurance oversight is a multi-dimensional problem. First is identifying which functions are automated and to what degree they impact the safety of the operation. Technology maturity should increase as the safety criticality of a function increases. Next is the operational environment in which the automated system is functioning, with lower risk operating environments providing the most flexibility for deployment of less mature technology and high-risk environments requiring the most mature solutions to support safe integration. Finally, the resilience of the system design and operation needs to be taken into account, with more resilient architectures (e.g., fail-safe, run-time assurance) providing opportunities for less mature technologies to be deployed in a safe manner.

Each of these problem dimensions has a spectrum of application, and each cannot be considered in isolation. For example, an operational environment will define the initial risk (e.g., rural linear inspection), but the automation of functions may depend on available infrastructure (e.g., ground-based DAA network) and equipage requirements (e.g., cooperative airspace). The wide variety in potential system architectures, functional allocations, and operating limitations provides opportunities for many diverse solutions to exist within the operational space. For safe integration into the airspace it is important that automated systems are well described in terms of their expected operational performance and functional limitations. These limitations combined with the right level of safety assurance oversight (per the operational risk assessment) allow for the evaluation of whether the technology implementing the function is mature enough for the operations in the proposed environment.

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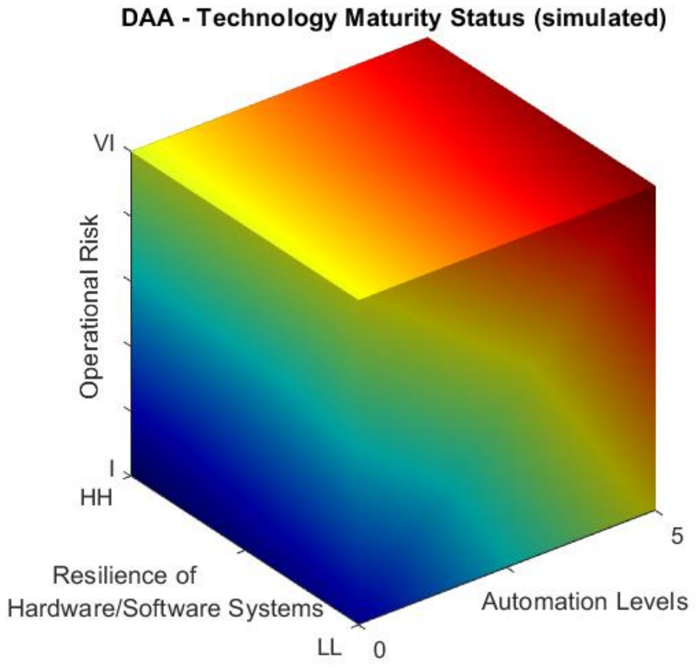
[17] EASA Artificial Intelligence Roadmap 2.0 published - A human-centric approach to AI in aviation | EASA (europa.eu)

[18] First public deliverable for Machine Learning Application Approval (MLEAP) research project - An EASA AI Roadmap 2.0 project | EASA (europa.eu)

[19] EASA releases its Concept Paper 'First usable guidance for Level 1 machine learning applications' | EASA (europa.eu)

Figure 1 – Example of technology maturity expectations for automated DAA (Red is high maturity, blue is low maturity)



Navigating across this spectrum of maturity can be complex with many trade-offs to consider when developing technology (e.g., limiting the operational environment while proving the resilience if a novel system architecture, constraining the autonomy of essential safety functions when moving into higher-risk operations). It is important for regulatory authorities to be clear on the expectations for demonstrating maturity (e.g., number of flight hours, design assurance processes, simulation/model data) as the technology is developed and the scope of operational deployments is expanded.

4.2.1 Automation Levels

The use of levels of automation has been common in proposed definitions and classification structures for automation, and when discussing the approach to the incremental adoption of automation technologies. While this concept provides simple language for thinking about automated vehicles, often the reality is much more complex. The JARUS approach to describing automation levels (see JARUS Doc 21) focuses on the relationships between the human and the machine and their associated responsibilities and control domains, and while at first glance the levels appear as high-level system descriptions the reality of automation is more nuanced. Ultimately systems aren't automated, rather functions are automated. These automated functions are then architected into a system which has to be evaluated. The JARUS approach will hopefully be instrumental in steering the community to a deeper understanding than the "levels" of autonomy and towards a functional approach to automation.

The structure and interconnection of automated functions in a particular operational architecture needs to be very clear to understand where safety critical functions exist and how automation impacts that safety criticality (see JAR Doc 21 on the methodology for evaluating functional automation). Each function may be at a different level of automation but when considered together as part of a broader Operational Design Domain (e.g., object and event detection and response) can be described using the same concept of automation levels. Again, the nuance of how this level determination is built up should not be lost, as the automation happens at the lowest functional level. When evaluating automation at a system level consideration should be given for functions associated with aircraft system autonomy and operational autonomy with intentional but possibly different approaches as the approach to approve these systems as safe for flight may vary in the absence of common industry standard implementations.

This use of automation levels must be carefully used and understood by both industry and regulators. Using “levels” can lead to oversimplification when looking at the total system. There are going to be individual functions at different levels, and it is likely some residual safety-related functions may never be fully autonomous, such as being responsible for the safety of an operation. To characterize a system as “fully autonomous” assumes all technology for the automation of all necessary functions is at an equal maturity (see 4.3section 4.3 below), which may not be feasible or viable for some civil aircraft because of technical and regulatory barriers that must be addressed. To support the development and understanding of existing automation architectures a methodical model must be used to assess what functions are feasible for automation today, and what capability gaps exist where functions still require human involvement because of a lack of technological maturity.

This link between technological maturity and the level of automation is realized via the operational risk. For lower risk applications (e.g., JARUS Cat A operations) the risk to the public of a failure or incorrect operation of an automated function may be managed by operational procedures (e.g., emergency response plans) and as a result the technological maturity of a particular implementation may be less well developed. In these inherently lower risk environments, the use of experimental or unproven technology is more acceptable because of the mitigations afforded by operational limitations. As the risk environment changes and the impact of functional failures become more severe, the maturity of the specific implementation of an automated function needs to mature to provide adequate assurance that a failure is within the acceptable safety bounds of the specific operation. The risk that automation poses or mitigates must be well balanced within the scope of the operational context to ensure that the right level of technology maturity has been demonstrated.

4.2.2 Operational Risk

Operational risk is the major delineator when it comes to assessing and approving technology for use in aviation operations. The JARUS operational risk framework identifies three general categories of risk in increasing order: Category A, B, and C (see JARUS Doc 09). This risk categorization scheme is further expanded on for Category B operations via the Specific Operational Risk Assessment (SORA JARUS Doc 06) which identifies specific requirements which need to be met in order to manage risk effectively. Finally, the risk categorization is expanded in Category C operations through the identification of higher-risk operations (e.g., commercial transportation of people and cargo) and defining the additional organizational, operational, and technical requirements which need to be met to be approved for operations.

Operational risk provides a valuable lens through which to view technology development and maturity. As functions begin to be automated, especially when using solutions which do not possess a clear design pedigree, their operations should be well bounded to assure that technical failures of the automated system do not lead to safety risks (e.g., run time assurance[20]). The evaluation of functions and how their automation affects safety can be assessed using the methodology describe in JARUS Doc 21. The aim of evolving technology maturity is to provide a stepwise approach to demonstrate capabilities of these automated functions in the appropriate risk environments such that they can be evaluated along with the redundancies and design/development assurance that may be used to support. Given that automation should be evaluated at the functional level its associated risk needs to be considered within the context of the ODD being evaluated (e.g., the higher-level DAA function vs lower-level Aircraft Detection function).

There may be cases where automated solutions are scoped to be operated only in higher risk environments. In these cases, the approaches to evaluating the technology for approval need to be well aligned to the risk-management expectations. In most cases these demonstrations are achieved via a design review approach (e.g., traditional type certification process using system safety assessments), or they may also be achieved through system verification demonstrations (e.g., through a Functional Test Based operational demonstration program with specified minimum flight hours). While both methods may provide the required data to support operational approval, gaining flight hours for a functional test-based demonstration has to be done in lower risk (e.g., well-controlled) operational environments. The sections below outline a general approach to scoping the types of operations that may be considered when developing/maturing automation technology.

Lower Risk

Lower risk operations provide the ideal environment for developing, characterising, and maturing technology. The inherent risks in these operations are much lower and as a result failure during experimentation can be managed much more effectively than in other risk environments. They provide flexibility with respect to failures and limit catastrophic outcomes when an airframe is lost. As a result these environments are ideal for:

a. System testing/verification;
b. Building flight hours in limited environments; and
c. Validating simulations/model results.

Medium Risk

Rising through the risk spectrum operations in mid-risk environments put more reliance on the correct function of technology and have fewer options for operational mitigation of risks. To be initially approved for operations in these environments the limitations of the automated functions need to be well characterized and understood (either via flight testing, using field data from lower risk operations, simulations and modelling, or through more traditional design assurance approaches for higher risk categories). Evaluation of the system architecture and where the automation has safety impacts (per JARUS Doc 21) is important in understanding the safety effect of automation in these

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[20] ASTM F3269-21: Standard Practice for Methods to Safely Bound Behavior of Aircraft Systems Containing Complex Functions Using Run-Time Assurance: https://www.astm.org/f3269-21.html

operations. Allowing operations in these environments provides for additional validation of simulation and environmental limitations. At the higher risk end of this grouping there are considerations for operations in ATM managed airspace and the maturity of the available and required ATM must be considered as part of the system architecture reviews.

Higher Risk

At the higher risk levels, mature technology is needed in order to gain initial operational approvals due to the strong interrelation between safety outcomes and technological performance (e.g., DAA systems). As a result, automated functions deployed in these environments should have mature technical architectures with good supporting design data. In most cases field experience (in lower risk environments) is a significant asset as it demonstrates the most maturity in system deployment. Simulations and models used as part of the evaluation and approval process must be well validated ideally with supporting data from field operations. Finally, in these operations the maturity and capability of the airspace systems and ATM support needs to be evaluated and assessed.

The use of automated functions as risk mitigations needs to be well balanced with the maturity of that technology with respect to the hazards which are being managed. When considering automated functions as risk mitigations the technology maturity should directly relate to the severity of the operational hazard being mitigated. As the severity of the hazard increases, so too does the need for the demonstration of maturity. In order to build confidence in automation as a risk mitigator the same paths to demonstration apply as above either via design and system architecture review of redundancies or through operational experience and the imposition of operational limitations while determining the limits of the technology.

4.2.3 Resilience of Hardware/Software Systems

Safety of flight is impacted by the ability of a specific implementation to continue to perform the function it is designed to perform. Continued safe operation in the face of degrading performance (e.g., environmental changes, equipment failures, data loss) can be considered the resilience of a functional implementation. The resilience of a particular solution is increasingly important as safety critical functions become more automated – the ability for a particular implementation to continue to respect airspace rules and limitations as well as avoid creating hazards to people on the ground is a core mitigator of operational risk. In general, the more resilient a solution is to errors or faults the better suited it is for implementing higher risk functions. There are numerous ways to drive resilience into a system (e.g., design assurance, run-time assurance, architectural redundancy) and each method should be considered for its appropriateness within any given operational and system architecture. Developing resilient operations supports the safety case in meeting robustness objectives.

Given that a resilient system is defined by its ability to continue the safe performance of its function, it can be quantitatively categorized using an approach similar to other standards (e.g., SAE ARP 4761[21], EASA Functional Test Based Means of Compliance[22]) via a probability of the loss of function. As functions become increasingly automated it becomes necessary to evaluate the status of the functions to

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[21] https://www.sae.org/standards/content/arp4761/

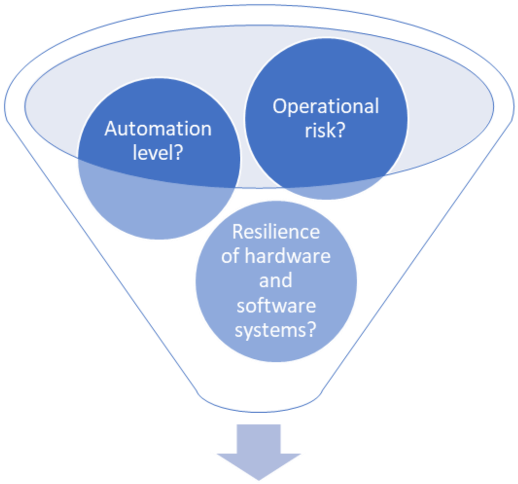
[22] https://www.easa.europa.eu/en/downloads/136564/en

effectively manage system safety. For systems which have the ability to determine functional status they can no longer perform the function (e.g., built-in-tests, run time assurance) and can annunciate that status (i.e., request a “take-over” of the function), a measurement of the number of take-over requests (ToR) per operational hour can allow for a qualitative categorization from low resilience (many ToRs/hour) to high resilience (few ToRs/hour). This concept of resilience (and the broader concept of automation trustworthiness) supports existing approaches to aviation system safety (e.g., design assurance, fault tolerant hardware) by providing an alternate perspective through which to view implementations which may not lend themselves to traditional methods (e.g., machine learning)

In evaluating whether a particular solution is mature enough for deployment, the resilience of the specific implementation plays an important role. The resilience of a system can be decoupled from the maturity of the individual technologies used to accomplish the task, but may in some cases be related, (e.g., a single-sensor implementation of a function would need very mature hardware to be considered highly resilient) so careful consideration of how technologies are combined to achieve a function need to be clear (e.g., the use of Run-Time Assurance to support Artificial Intelligence). The use of low maturity solutions in higher risk operations implies a need for more resilient system architectures when automated functions are operationally critical, but this must be carefully balanced against other risk factors and functional solutions. These kinds of trade-offs are implementation and operation specific and will benefit from future standardization.

Figure 2 – Example of Assessment Criteria to Evaluate Maturity Requirements

Example of the measurement or classification of the status of the Technology Maturity related to DAA systems to be applied in autonomous navigation based on the combination of the 3 variables: the weight of each variable must be determined



DAA Technology Maturity **degree** for approving autonomous operations [LL_{DAA} L_{DAA} H_{DAA} HH_{DAA}]

4.3 Evaluating Maturity/Maturity Models

Using the dimensions of an automated operation described above the question of whether a specific technology can be safely employed in a particular operation will ultimately depend on the maturity of the specific technologies. Maturity refers to the state of a technology (or set of technologies) which has an experiential pedigree (either through real-world operations, or experimental testing) along with the evaluation and analysis of data (including validated models and simulations). The greater the certainty around the behaviour of the technology the more mature the solution can be said to be. There are many approaches to evaluating, developing, and demonstrating the maturity of aviation systems (e.g., SORA Annex E Functional Test Based approach), and each of these maturity models and approaches has merit when being considered for implementation. When looking to adapt the models to automated operations there are additional considerations that may need to be taken into account to help with prioritization of maturity and understanding the relationships to human-machine interactions (e.g., integration and dependency of system functions, fallback mechanisms, human-machine interfaces).

Mature technologies are needed in order to clarify the uncertainty when integrating a particular operation into an airspace. Transparency between airspace users, infrastructure/service providers, and other automated systems is essential to managing safety. In order to effectively reduce the uncertainty associated with any set of operations, the capability and limitations of aircraft and operational support systems (automated or otherwise) need to be well described, which can only be accomplished through technologies whose maturity is commensurate with the operational risk. Annex 1 contains suggestions for specific considerations when incorporating automation into a concept of operations. Some approaches to describing and developing technology maturity in support of the concept of operations are described below.

4.3.1 NASA Capability Maturity Model

4.3.1.1 *Capability Maturity Model for Automation*

A methodical and robust process for achieving automation capability maturity and for evaluating potential gaps in technology, data sources, and the governing civil regulations must be applied throughout the design, development, testing, certification, operational approval, and airspace integration of any new automation capability.

To address this challenge, the National Aeronautics and Space Administration have conceptualized a Capability Maturity Model (CMM) structure, and a gated automation evaluation process[23]. Both are intended to provide a common structure under which the aviation industry can honestly evaluate the technical and regulatory maturity for automation functions being proposed for aircraft automaton and operational autonomy.

Though aircraft automation and operational integration are inextricably tied to each other, they are often evaluated separately, and in a serial manner, during design and development and during certification. This is partially because of the challenge of designing a system and then evaluating how it works in operational service, and because the aircraft and its operational certification are often evaluated by separate parts of civil authorities with different and often mutually

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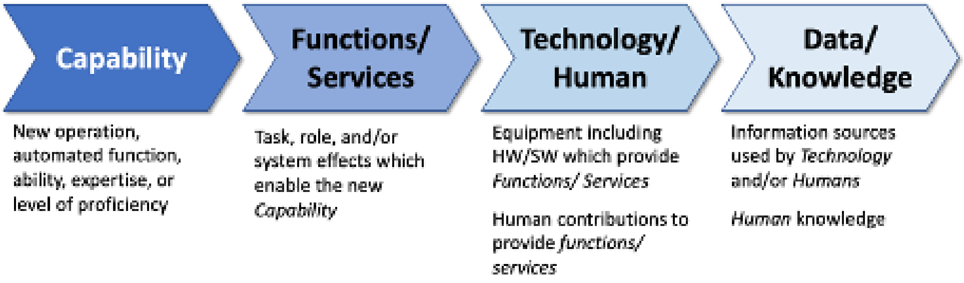
[23] https://aam-cms.marqui.tech/uploads/aam-portal-cms/originals/da85f1b4-b18d-48aa-8db6-b3b0df85c99f.pdf

exclusive processes. This presents a growing challenge for the human-machine interface and resilient design of automation that replaces traditional pilot function, particularly as this automation is envisioned to perform capabilities tied to operational integration that are the legal responsibility of air traffic controllers, dispatchers, and other human elements in the system.

The development of any new automation capability must be evaluated in the context of the type of aircraft, its operational mission, the specific elements or segments of that intended mission, the airspace it is intended to fly in, the clearly defined role of the human (for normal and abnormal operating conditions), and the level of expected safety that must be achieved to be accepted by civil aviation authorities who are charged with protecting the public. Therefore, one must assess the maturity, as well as the accuracy, availability, integrity, continuity, and coverage of data sources and technology to implement an intended function in support of a new capability.

Figure 3 shows the notional FSF/NASA proposed capability maturity model structure. The model ties the proposed automation capability (a new operational concept, a new aircraft/system function, or other) to the functions and services that will enable the new capability. These functions and services are tied to the core technology that will enable them, and to the clearly defined role of the human regarding their expected contribution to the function or service. The technology that enables the proposed functions or services are in turn driven by data and information sources that are required for the technology to perform its intended function. Without this entire thread being evaluated and clearly understood, it is possible to envision new automation capabilities whose intended functions that cannot be supported by current technologies and data sources. It may also be possible to envision new automation capabilities that are beyond the knowledge or skill for a human to perform the necessary role to safely team with the new automation capability.

Figure 3 – Notional Capability Maturity Model for Evaluating Automation

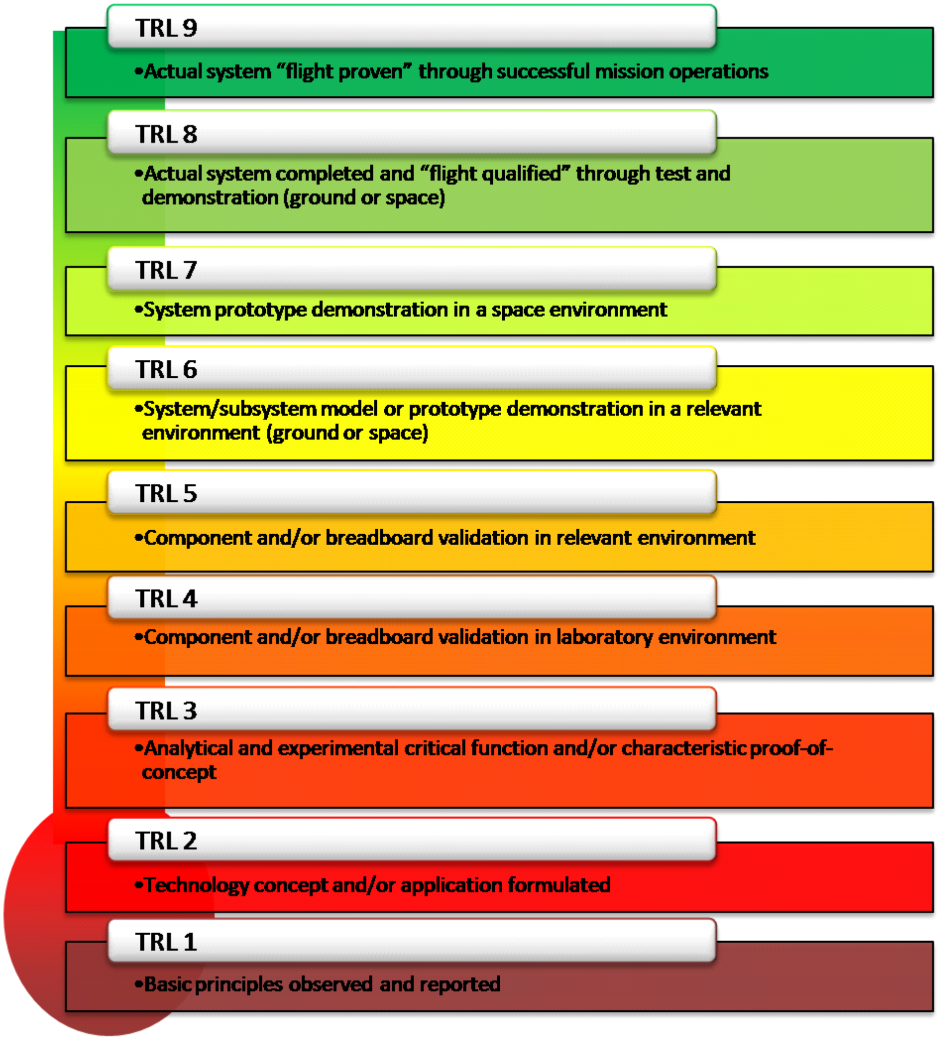


4.3.2 Technology Readiness Level Categorization

One common way to assess the readiness of tehcnology for deployment is to use the Technology readiness level (TRLs), developed by the National Aeronautics and Space Administration (NASA)24. TRL provides a measurement framework for assessing the maturity of a particular technology. The nine TRL levels enable consistent and uniform communication of a technology's state of maturity, with TRL 1 representing the lowest level of technical maturity and TRL 9 the highest.

The TRL levels are described in Figure 4 below.

Figure 4 – Technical Readiness Level Descriptions



TRL can be used to describe the maturity of a particular automated technology/system in a specified operational environment (or ODD) though it

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[24] https://www.nasa.gov/directorates/heo/scan/engineering/technology/technology_readiness_level

must be accompanied by evidence supporting this assessment. While there are not specific standards describing how to demonstrate a particular TRL (as each technology will be different based on the scope of its intended function), the intention is to mature the technology through operational evaluations and collecting evidence of its capabilities and limitations.

While the TRL concept applies to the development of any technology, it does not directly consider its application within a particular system architecture, nor does it consider the criticality (for safe or continued operations) of the solution. TRL must be applied within a holistic operational approval framework that considers the entirety of an operation or domain of operations (e.g., JARUS SORA, Standard Scenarios). Utilizing these types of approval mechanisms TRL must be communicated by the designer/manufacturer of the solution in support of operators looking to apply the technology. This relationship between designer/manufacturer and operator is critical especially when deploying lower TRL solutions.

5. Conclusions: Regulatory Impacts

Traditionally incorporation of automation within the airspace environment has been incremental and focused on providing improvements to the efficiency of operations. The introduction of UAS into the airspace system has disrupted the traditional approach to technology adoption, and as a result aviation regulators and professionals have had to adapt new frameworks to support the integration of these operations. As these frameworks are being implemented it is important to recognize the role that automation will play in enabling the success of routine, efficient, and safe integration of all aircraft in supporting operations. This paper has identified a number of the challenge areas related to the regulatory environment that need to be assessed and integrated into approval frameworks including:

1) Updates to existing definitions of flight rules to accommodate aircraft with varying degrees of automated behaviour and piloting concepts;
2) Considerations for incorporating automated capabilities into the existing airspace structure, and how that structure may need to evolve to support different operational concepts;
3) Development of automated infrastructure in support of future operations including aerodromes and traffic management systems; and
4) Pathways to establishing the maturity of technology and the regulatory environment in support of automated operations.

It is recognized that there will not be a single solution to incorporation of automated capabilities across the airspace, but this document lays out a common path forward for the development, evaluation, and implementation of these capabilities into existing operational frameworks. The document also proposes a vision of a data centric airspace leveraging proven technologies to continually improve safety and efficiency through the deployment of automated systems in conjunction with human oversight and safety management systems. Several jurisdictions have already begun to implement these concepts to varying degrees in their existing aviation roadmaps, and future concepts of operations including the United States[25], European Union[26], United Kingdom[27], and Japan[28]. As these concepts mature and incorporate automated operations at scale there will be opportunities to harmonize the systems to enhance safety, improve efficiency, and expand access to aviation services.

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[25] https://www.faa.gov/sites/faa.gov/files/Urban%20Air%20Mobility%20%28UAM%29%20Concept%20of%20Operations%202.0_0.pdf

[26] https://www.sesarju.eu/node/4544

[27] https://eveairmobility.com/uk-consortium-completes-urban-air-mobility-concept-of-operations-for-the-civil-aviation-authority/

[28] https://www.mlit.go.jp/common/001611491.pdf

Annex 1: ConOps: Elements of Automation

The ConOps allows the applicant to communicate the bounds of the operation so that hazards can be identified and mitigated as part of a Safety Risk Management (SRM) process. The inclusion of autonomy as a component of the ConOps triggers the need for additional considerations in several areas:

Organization overview

Safety

Organizations should be able to convey how the development lifecycle of their autonomous systems are linked to their Safety Management System (SMS) processes, specifically the SRM and Safety Assurance (SA) pillars.

Security

Considerations for the operational ecosystem, data links, data integrity checking, software chain of custody, package chain of custody, operator personnel vetting, passenger vetting, production component chain of custody, tamper indications, etc.

Software development employing a DevSecOps approach

Design and Production

Processes for algorithm training, data set collection and curation, application of simulations, interface standards … all need to be considered as these will have an impact on the assurance, integrity, and authority that can be assigned to the autonomous execution of a function

Human Engineering

From an autonomy perspective, the operational environment and the interaction between the human and the autonomy does not have the same established level of maturity as traditional piloted operations. It follows, that personnel with a human factors background will initially play a larger role in the design of the interfaces

Personnel Training

Personnel training must be structured for consideration of the interaction between the operator and the implementation of the autonomy which will vary based on the criticality of the function as well the level of authority the operator will retain in the interaction.

Maintenance

As part of a Safety Management System (SMS), Maintenance must account for data analytics components that support Safety Assurance of autonomy performance. Data collection, reduction, and storage procedures and resources will support the analysis and system assessments that can identify needed corrections. The corrections will feed back into the Safety Risk Management

Crew

Crew Resource Management will need to consider the implementation of autonomy in the operational context. Considerations for the distinction between action and decision making and which, human or autonomy, is accountable for each.

UAS Configuration Management

The performance of algorithms implementing autonomy tend to improve (within the scope of their design) with additional data applied to their training. As operations commence and actual data is collected, there is a benefit to applying this newly collected data to improving the performance of the algorithm in execution of the ConOps. Mechanisms need to be in place for managing this data and to establish the process for incorporating, verifying, and validating such improvements.

Operations

Standard Operating Procedures (SOPs)

Operational limitations specific to the performance of the autonomous system should be clearly stated.

Normal

Preflight – The Pilot-in-Command (PIC) is accountable for the flight and therefore the performance of the autonomy in execution of that flight. There should be a clearly documented process for pre-flight verification of UAS air and ground equipment, and any external systems necessary for the autonomy to function as intended.

Wherein the autonomy is implemented for functions during various phases of the flight operations, the document should clearly denote the responsibility of the PIC, by acknowledging both the decision making and action execution authority that the autonomy is being granted in Normal, Contingency, and Emergency operations.

Any run-time-assurance (RTA) implementation details should be captured as well.

Abnormal and Emergency

Any changes to the authority granted to the autonomy in decision making and action execution from Normal operations should be specified.

Run-time assurance states that may be triggered for Abnormal and Emergency operations should be specified.

Accidents, incidents, and mishaps

The scope of data available and collected should be sufficient to ascertain the state of the autonomous system so as to facilitate root cause corrective action activities.

Training

General information

Initial training and Qualification

Training must consider the interactions between the operator and the autonomy with considerations for off nominal performance: latencies, degradation of autonomy sensor performance.

Training should focus PIC awareness on areas where there is increased potential for the autonomy to undermine their effectiveness of maintaining an accurate mental model/situational awareness of the system's state while in operation[29].

Where applicable transition from autonomous operation to PIC control should be exercised, and of course, in the most challenging workload scenarios that can be expected operationally.

Procedures for maintenance of currency

Flight Simulation Training Devices

Simulators should have the ability to convey adequate fidelity to match operational interactions in

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[29] https://www.icao.int/Meetings/A40/Documents/WP/wp_296_en.pdf

actual time durations, facilitate the full spectrum of potential failure modes of the autonomous subsystems, appropriately trigger RTA actions, and represent the full scope of interactions between the autonomy and the operational environment.

Training program

Consider integration of Human Engineering and mechanisms for capture of operator feedback towards continuous improvements of the operator / autonomy interfaces (i.e., transparency of autonomous actions, trend information, fault indications, etc.) and to identify behavioural safety risks.

UAS Description

UA

Aircraft Performance Characteristics

Identify subsystems enabling autonomous operation

Identify the operational design domains for autonomous functions

Identify any RTA behaviour triggers and state transitions

Sensors

Convey sensor role in autonomous behaviour

Identify effects on autonomous behaviour when experiencing degraded performance

Payloads

Identify any reliance of payload (e.g., Electro-Optical (EO) camera) that support autonomous operations directly or are considered a method to enable the PIC to effectively supervise the autonomous operation or that supports the PIC’s ability to effectively transition to active control of the UA.

UAS Control

General

Navigation

Convey dependency of UAS on external/internal navigation system to maintain effective performance of autonomy

Convey impact of degradation or loss of navigation system to autonomous operations

Convey thresholds for normal performance of navigation systems required for autonomous operations

Autopilot

Flight Control System

Control Station

Convey interfaces that support PIC interaction with autonomous operation.

Convey interfaces that indicate degrading state of autonomous operation or, as applicable, where operational control may transition to the PIC

DAA

Convey DAA system description and integration with autonomous operations and the operational design domain limtations for those operations.

Convey impact of degradation or loss of DAA system to autonomous operations

Convey thresholds for normal performance of DAA system required for autonomous operations

Geo-fencing

Identify any behaviors with the interaction between a geo-fencing capability, the autonomy, and the limits of the operational design domain (e.g., transition control to PIC, autonomy has authority to change course, etc.)

GSE

Identify any data acquisition and storage systems that support autonomy development

C2 Link

Degradation – Convey how autonomy is affected and what the behaviors will be when experiencing a degraded C2 link

Loss – Convey how autonomy is affected and what the behaviors will be when experiencing a loss of C2 link

Safety Features

Describe any safety features designed in to the autonomy including: GCS interface standards, implementation of RTA and the details of the fall-back states, System design features (e.g., redundancy, independence, …)