UK Research and Innovation

Future Flight Initial Aviation Safety Framework

Briefing report for UKRI

July 2021

egis

University of York

Contents

Executive summary

This report analyses and documents the potential developments in future flight that will influence safety and identifies the activities required to address the safety impacts especially those that will have a significant impact on the development of the future aviation system. It has been produced by Egis and the University of York under contract to UK Research and Innovation (UKRI).

The analysis was structured into a set of future scenarios using actor diagrams as pictorial elements. These represent the evolution of the (future) aviation system over different time horizons (short-/medium-/long-term). Within the scenarios, use cases have been defined. The use cases describe the primary applications of new flight technology which are relevant to the scope of the Future Flight Challenge (FFC). In addition, a set of transversal themes were also defined which are relevant across all scenarios and use-cases. The transversal themes are topics which are considered to have a significant impact on future aviation safety.

The use cases selected for the project were:

- Use case 1 - Drones, which comprises three sub-use cases: drones for delivery, drones for inspection/monitoring/broadcast and drones that perform robotic functions (e.g. repair, crop spraying)
- Use case 2 - Urban Air Mobility (UAM)
- Use case 3 - Regional Air Mobility (RAM)

Four transversal themes were also identified for the project:

- Safety management of complex systems
- Integrated risk and safety management
- Role of the human and autonomy
- Supporting infrastructure

The analysis addressed safety impacts across the governance, organisational and technical layers. This was performed through application of the safer complex systems framework developed by Engineering X at the strategic level and complemented by use of bowtie analysis to analyse hazards and controls at a more detailed level.

These complementary approaches led to a set of recommendations placed on different stakeholder groups and supplemented by requirements placed orthogonally on functions and capabilities of the key elements of the future aviation system. A detailed analysis of the key safety management challenges associated with the four transversal themes added further recommendations at the strategic level.

The output of this project comprises an initial safety framework, with a particular focus on the top layers of the argument and constructed in the goal structuring notation (GSN) language that is familiar to many safety professionals. The framework is defined at the strategic level and this report provides the key contextual elements of the framework as well as setting out the claims and evidence required to be produced as part of future work.

The analysis concludes with a presentation of the highest priority recommendations to address as the first steps in setting out a programme of safety work for future flight operations:

Recommendation 9.1 – Development of a concept of operations for the future aviation system which includes transitional states.

Recommendation 9.2 – Establishment of Target Levels of Safety for aircraft operations, including specific future flight use cases.

Recommendation 9.3 – Establishment of an aviation system risk baseline made up of both the current risk profile and the future expected risk profile, based upon future concepts of operations.

Recommendation 9.4 – Prioritisation of the issues and recommendations in the report and the establishment of a safety work program in support of the FFC. This should include, amongst other things, a plan for managing the impacts of complex systems at the Governance, Management and Task/Technical layers.

This should also include consideration of the many more detailed recommendations in this report. Consideration should be given to placing the responsibility for developing and delivering this plan on a pan-industry body or, establishing one specifically for this purpose.

It should be noted that this briefing pack comprises a summary of the content from the main report and therefore numbering of certain sections and recommendations is carried across here to ensure continuity between both documents. Given it is a summary, not all recommendations are listed here. A full list of recommendations is captured in Appendix D of the main report.

Context, background and introduction

Context, background and introduction

Context

Developments in future flight (FF) are leading to potential fundamental changes in the aviation safety risk landscape. It is necessary to understand these potential changes and to respond to them in the design of the future aviation system including the regulatory environment, safety management processes and mitigating actions.

This report analyses and documents the potential developments in FF that will influence safety and identifies the activities required to address the safety impacts especially those that will have a significant impact on the development of the future aviation system. It has been produced by Egis and the University of York under contract to UK Research and Innovation (UKRI).

Background

The Future Flight Challenge (FFC) is a UKRI initiative that will support the development, in the UK, of new aviation technologies such as freight-carrying drones, urban air passenger vehicles and hybrid-electric regional aircraft that will transform the way that people and goods fly. The challenge will also support the development of the necessary ground infrastructure, regulation and control systems required to use these new aircraft safely.

The FFC programme identified that, as new aircraft and systems are introduced, the aviation safety risk landscape would potentially change fundamentally. Autonomous aircraft will mix with electrically powered vertical take-off and landing (eVTOL) air taxis and drones in a myriad of applications. Not only will the types of risk change but the way they are assessed and managed may have to change to maintain or enhance the required level of safety. The FFC therefore contracted a study to investigate this issue and to determine what actions need to be taken to ensure that safety can be appropriately assured in the future environment.

Introduction

The nature of the FFC is such that an extremely broad range of topics could potentially be included within the scope of this work. It was therefore necessary to focus the effort on a set of areas considered to be most relevant to future aviation safety. In particular, the focus has been placed on areas that match the objectives of the FFC programme in promoting the UK's role in building, using and exporting greener and more efficient modes of air transport through advances in electric and autonomous flight technology.

To structure the analysis, a set of future scenarios was defined representing the evolution of the (future) aviation system over different time horizons. These scenarios represent a realistic progression of the technological, operational and regulatory aspects of the aviation system as it seeks to address the transport needs of society into the future in a cost-effective manner. However, the uncertainty associated with the definition of the future scenarios increases proportionately with the distance from the present time.

Within the future scenarios, use cases have been defined. The use cases describe the primary applications of new flight technology which are relevant to the scope of the FFC. In addition, a set of transversal themes were also defined which are relevant across all scenarios and use-cases. The transversal themes are topics which are considered to have a significant impact on future aviation safety. These themes may also be relevant to innovations in the 'traditional' aviation space of large air transport vehicles although this is beyond the scope of the FFC and this report.

This approach allows for different categories of use-cases to be represented whilst also recognising that certain core themes related to technology development and risk management will also evolve across those horizons.

Scenarios

Three future scenarios are defined:

- Short-term horizon (approximately year 2025)
- Medium-term horizon (approximately year 2030)
- Long-term horizon (approximately year 2035)

Use Cases

The use cases selected for the project were:

- **Use case 1 –** Drones, which comprises three sub-use cases: drones for delivery, drones for inspection/monitoring/broadcast and drones that perform robotic functions (e.g. repair, crop spraying)
- **Use case 2 –** Urban Air Mobility (UAM)
- **Use case 3 –** Regional Air Mobility (RAM)

Transversal Themes

To ensure key safety challenges are identified and addressed early in the evolution of UK aviation, transversal themes were identified which are likely to have the greatest impact on safety across all use cases. Four transversal themes were identified for the project:

- Safety management of complex systems
- Integrated risk and safety management
- Role of the human and autonomy
- Supporting infrastructure

Scope

The scope of the project focuses on operations that are within the purview of the FFC activity, i.e. drones, UAM and RAM. The following operations are out of scope:

- High Altitude Platforms (HAPS) and associated operations
- Space vehicles and associated operations
- Activities covered by other programs such as Jet Zero[1] and FlyZero[2], including future developments of supersonic, transatlantic and larger passenger carrying aircraft

Note that while these operations are out of scope, many of the concepts discussed in this report will relate to, and can be applied to, these operations.

1. *Jet Zero Council: Government unveils new collaborative initiative to decarbonise aviation*
2. *ATI Launches FlyZero Initiative*

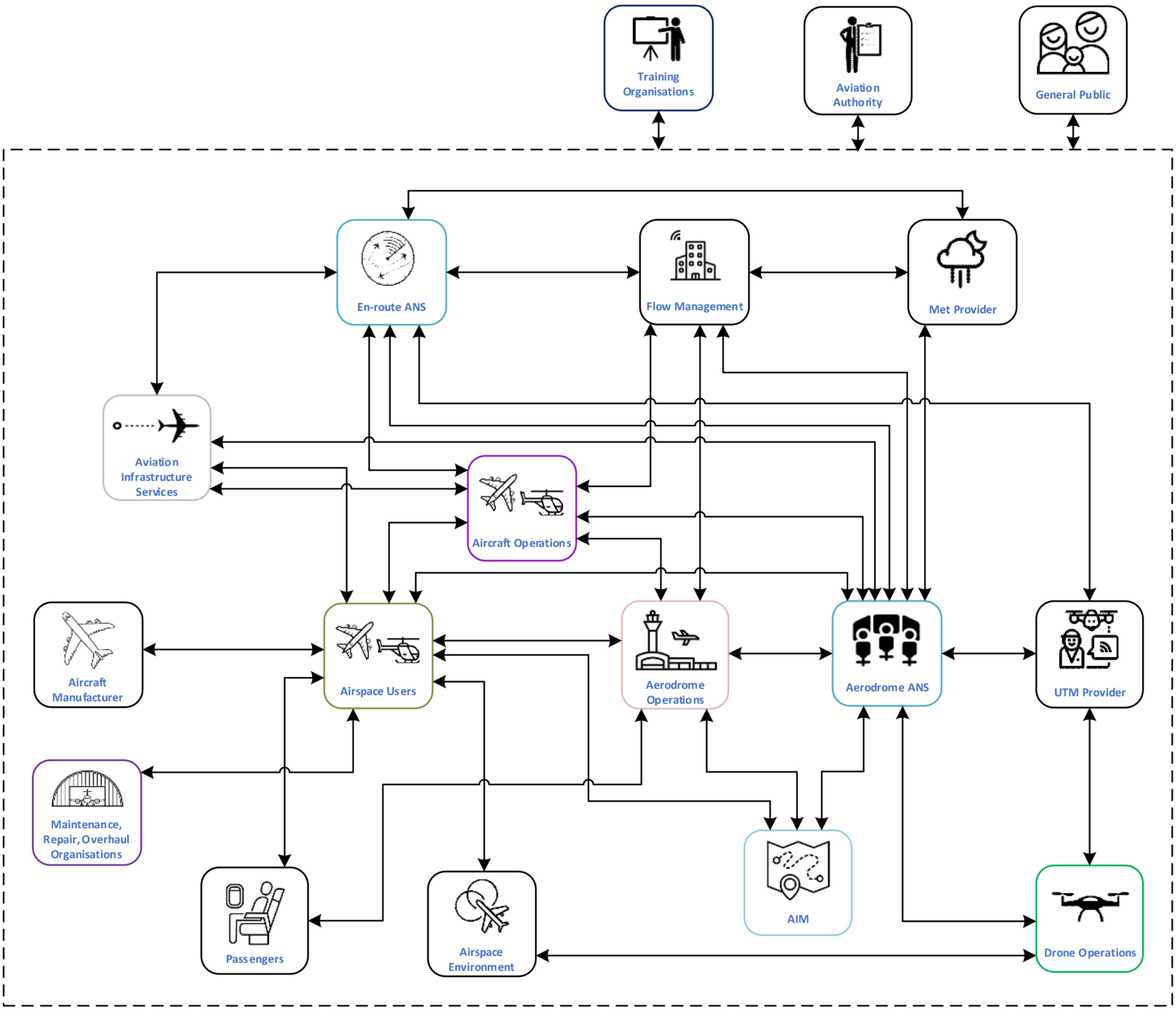
Current aviation system

Stakeholders and interactions

The stakeholders in the current aviation system are numerous, with interactions occurring between many of them. These stakeholders and their main interactions are shown in the actor diagram.

The current system is characterised by airspace users using portions of the airspace in a controlled and regulated manner. Air navigation services (ANS) for airspace users in controlled airspace are provided by a combination of enroute and aerodrome service providers depending on the part of the airspace the airspace users occupy. The ANS relies on a combination of support and infrastructure information services to operate effectively.

In the current aviation system, conventional aircraft and drones are operated in a segregated fashion with separate operating organisations and separate traffic management providers. Drones do however use the aerodromes as a base for operations and there are specific capabilities for drones within both aerodrome operations and infrastructure services to support their operation and the safe interaction between drones and conventional airspace users.



The diagram is structured into a central portion (enclosed by the dotted line) which shows the main elements and interactions. Some of the main elements are expanded into groups on the next page which sit outside the dotted line to provide additional detail.

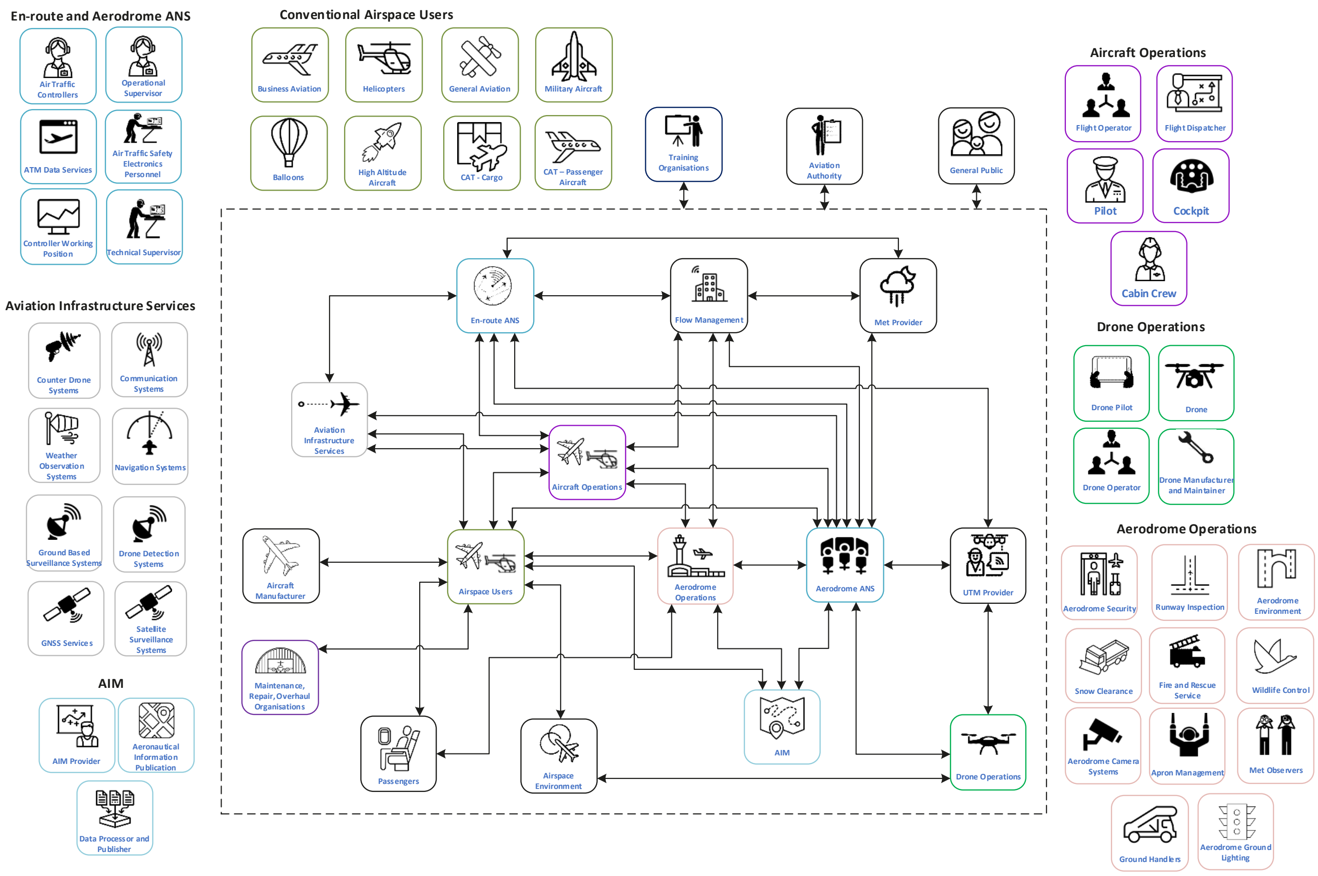
Expanded view

Below, some of the main elements are expanded into groups which sit outside the dotted line to provide additional detail.

Airspace users are supported by a range of support services such as maintenance, repair, overhaul (MRO) and by the aircraft manufacturers. Airspace users are usually supported by aircraft operating organisations, e.g. airlines.

Aerodromes are also supported by aerodrome operating organisations providing the necessary functions to support operation of the aerodrome.

Conventional airspace users comprise fixed-wing and rotary wing aircraft operating on a commercial and leisure basis. This group also includes military aircraft.



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The future aviation system

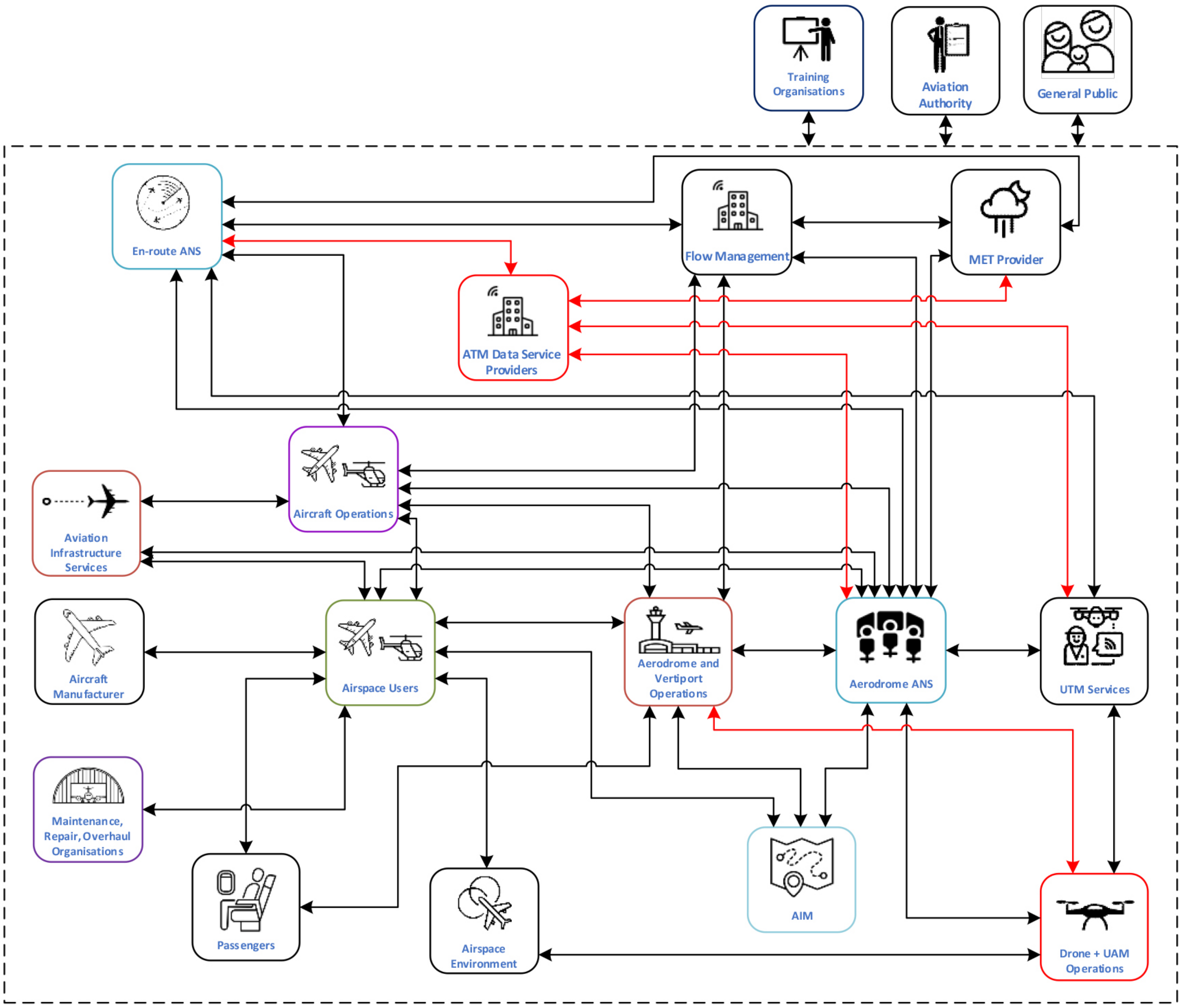
Short-term scenario

This diagram shows the expected changes to the aviation system within the short-term (approximately five years). The changes from the current scenario actor diagram are shown in red.

This scenario is characterised by early adopters of drone and UAM aircraft operating on a limited volume basis within the current regulatory and airspace structure. Requirements for certification and aircraft approval will be similar to today's environment. New aircraft will generally operate below 2,000ft Above Ground Level (AGL) (and 400ft AGL for drones), in Class G airspace (under current procedures) or portions of controlled airspace that are either segregated from other airspace users or where positive separation is assured through existing procedures (e.g. for UAM aircraft flying under Visual Flight Rules (VFR) in controlled airspace).

It is anticipated that any form of new technology will be limited in terms of functionality (range / capacity etc.) and automation will be limited to operating in an assistive capacity similar to current autopilot and automatic landing functions.

The existing aviation infrastructure will remain, at this stage, largely unchanged. Drones and UAM aircraft will operate in a limited capacity within the existing infrastructure with a pilot in command (PiC) either in a remote or on-board capacity. Drones will increase in number and variety of operations more quickly compared to UAM aircraft.



Expanded view

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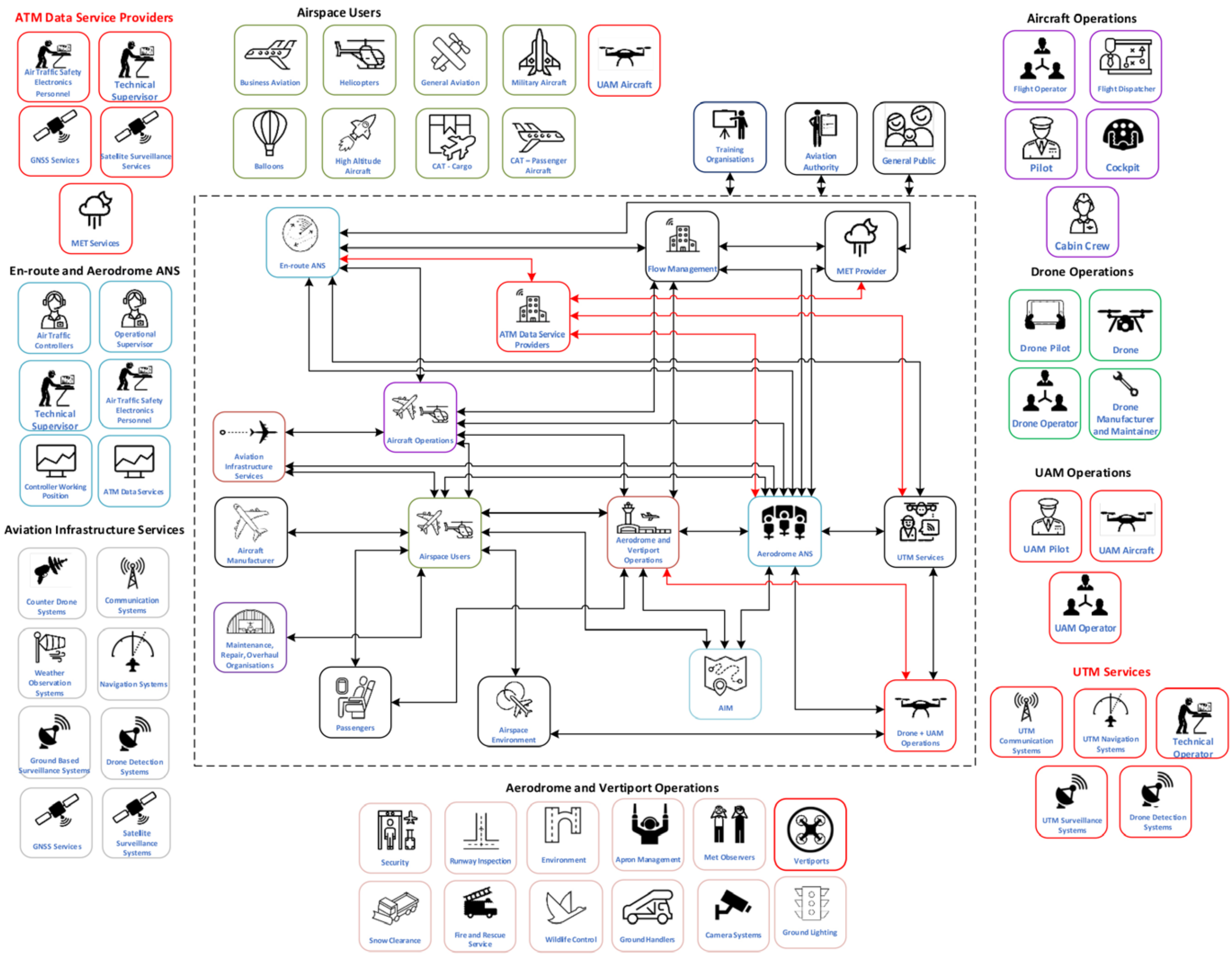


Synopsis

The key changes between now and the short-term future are the introduction of:

- ATM Data Service Providers (ADSPs), including different types of service provider.
- UAM Operations.
- Vertiports (the area of land, water, or structure used, or intended to be used, for the landing and take-off of VTOL aircraft together with associated buildings and facilities).
- UTM services as a more generic term to replace UTM provider.

The introduction of ADSPs is currently being investigated under European initiatives such as the Airspace Architecture Study[3] and the Wise Persons Group report[4]. The scope of these providers has not yet been fully established, but it is expected that a number of services could be provided. This could include, but not be limited to Meteorological (MET) services, satellite-based surveillance (such as Automatic Dependent Surveillance – Broadcast (ADS-B)), or other flight data information.

The introduction of UAM aircraft is expected to occur in the short-term, for example with introduction of at least one planned in 2024[5]. Initially they may operate from existing aerodromes, however new UAM ground-based infrastructure known as vertiports will also start to be established to support an expanded range of operating locations. The growth of UAM will need to be matched by deployment of the supporting infrastructure (e.g. vertiports and dedicated traffic management services). UAM services may be scheduled or on-demand.

3. SESAR Airspace Architecture Study
4. Report of the Wise Persons Group on the Future of the Single European Sky
5. Vertical Aerospace Reveals 'VA-1X' Air Taxi, Targets 2024 for Commercial Operations

BVLOS operation for drones will be common and some operations will rely on autonomous, rather than remote pilot, control.

Supporting industries will also change and evolve in this timeframe. This could include, for example, changes in the insurance industry, weather forecasting and obstacle survey services.

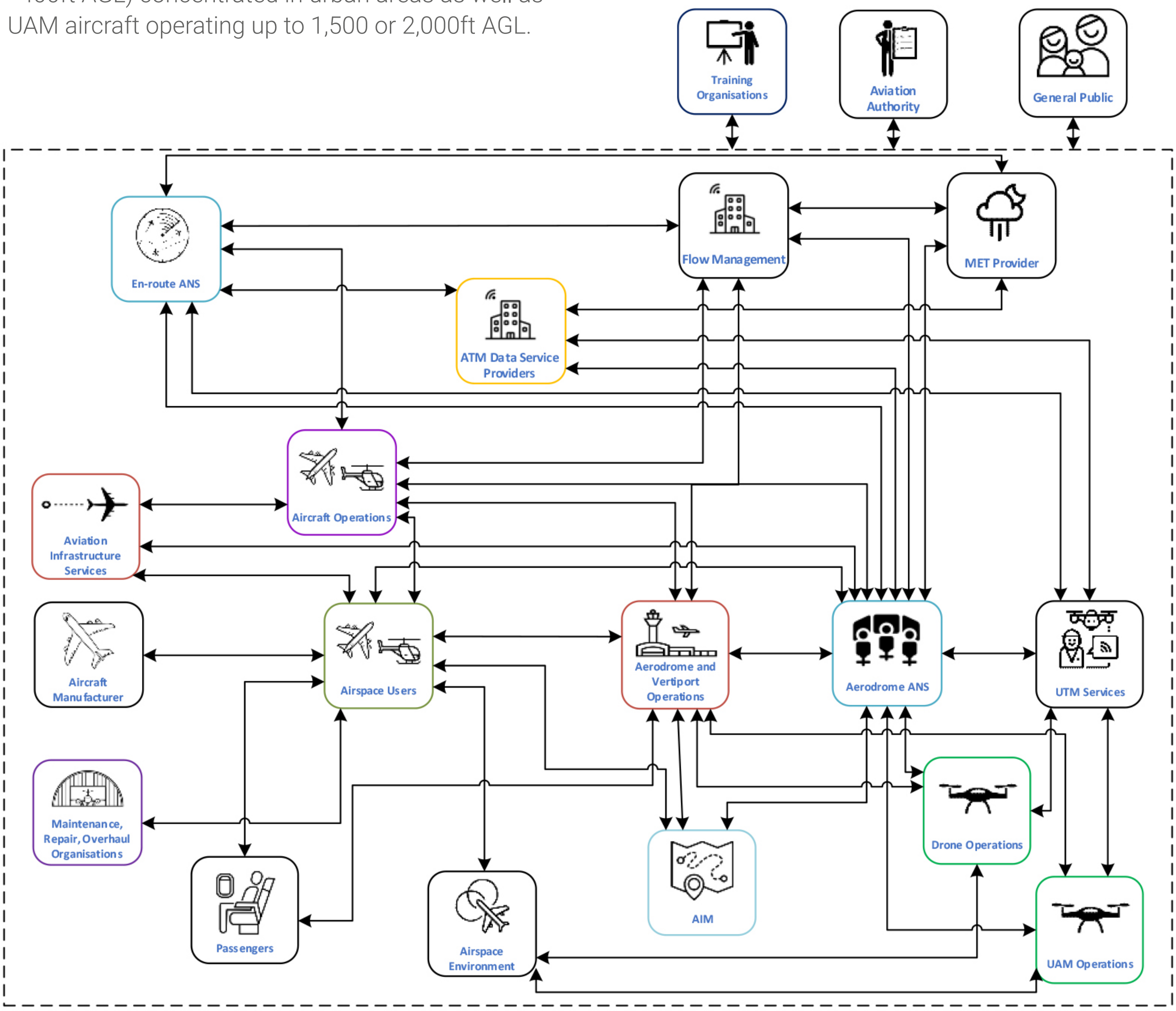
Medium-term scenario

This diagram shows the expected changes to the aviation system for the medium-term, i.e. up to approximately 10 years. The changes from the short-term actor diagram are shown in red, with the main changes being the introduction of RAM operations and the evolution of more services in ADSPs and ANS.

This scenario is characterised by more widespread and higher density use of drones and UAM aircraft operating with increased use of autonomous functions. The regulatory and airspace structures will evolve to meet the demands of higher volumes of drones operating in very low level (VLL) airspace (i.e. <400ft AGL) concentrated in urban areas as well as UAM aircraft operating up to 1,500 or 2,000ft AGL.

This scenario is also expected to include a limited volume of aircraft for inter-city journeys (over 100 miles). These journeys will involve larger aircraft operating with electric or hybrid propulsion with or without Vertical Take Off and Landing (VTOL) capability at altitudes above 2,000ft AGL. Given the longer distance nature of this use case, the aircraft are expected to operate predominantly on a scheduled basis with less use of on-demand services.

The physical and digital infrastructure will develop to accommodate the needs of these new types of vehicle with construction of multiple vertiports in urban environments where demand is expected to be greatest. It is likely that smaller airfields (e.g. today's GA-only airfields) will also become more widely used for operations of new aircraft types alongside existing uses. Supporting infrastructure, including traffic management systems, will need to have the ability to cope with on-demand as well as planned services.



Synopsis

The infrastructure supporting 5G mobile communications link and more widespread satellite-based communications links will be present albeit some of these will be in an immature state. It is expected that electronic conspicuity (EC) for all aircraft types, including GA, will become more important and potentially mandatory as a mechanism for enabling detect and avoid solutions to be effective, as well as more strategic forms of separation (e.g. traffic/flow management).

This scenario will also lead to the formal designation and segregation of airspace at VLL and the introduction of UAS and UAM service suppliers, e.g. UAS traffic management (UTM) service providers, operating in a unified fashion with existing ATM service providers (although not yet in a Unified Traffic Management Service (UnTMS)). The concept is shown below.

These service providers will share information bilaterally as necessary to improve the efficiency of the ATM service and permit entry on an exceptional basis of UAS aircraft into airspace normally occupied by manned aircraft. UAM aircraft will be subject to the same ATM service as other aircraft operating in controlled airspace due to the nature and location of operations.

The airspace and regulatory structures will evolve to meet the needs of the emerging UAM and drone sectors although these factors may hinder a faster pace of adoption of these technologies into the aviation sector.

Some challenges are expected to emerge related to the provision of safety assurance for the new platforms and service providers to meet the necessary safety requirements. For example, in this timeframe, there may be more composite aircraft that do not provide a primary radar return entering high-density airspace where primary radar has an important safety role. Also, autonomous vehicles may start to be deployed and mix with traditional manned aircraft. The new entrants may be high-technology start-ups that do not have a corporate knowledge of traditional aviation procedures or culture.

There will be limited integration of airspace structures between manned and unmanned aircraft, although the UAS traffic management function will develop rapidly to support this transition.

In the medium-term, drones, UAM and RAM aircraft will develop further, with increased levels of infrastructure and service provision made available. This will include more physical infrastructure for UAM aircraft such as "Vertiports" and adaptation of existing infrastructure (e.g. providing hydrogen storage at conventional aerodromes). Some aerodromes may become 'service centres' for UAM aircraft where they can be parked safely overnight, hangered and maintained by qualified personnel.

ATM and UTM service provision will evolve to provide a greater range of services to the new vehicles. This will include Communications, Navigation and Surveillance (CNS) infrastructure specifically for UAM and drones alongside the necessary technical staff required to operate these systems.

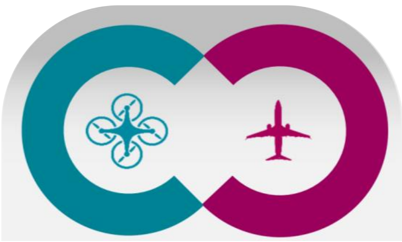
Another change in the medium-term is the addition of more advanced Traffic Management Systems. It is predicted that in future the role of Air Traffic Controllers (ATCOs) will evolve to a supervisory role, where they will be required to act in the event of emergencies, rather than providing continuous active control. Increased dependability in ATM systems will be needed to address integrity, resilience and cybersecurity challenges posed by greater automation. These systems will become more active in the medium-term; however, the evolution of the ATCO will not yet be complete and so they will still remain as important stakeholders in the aviation system.

Unified Approach

A holistic policy, regulatory and legal perspective to traffic management encompassing both unmanned and manned traffic systems

UAS Traffic Management

Designed for unmanned aircraft, providing the necessary information and procedures to enable safe flight in shared and segregated airspace.



Air Traffic Management

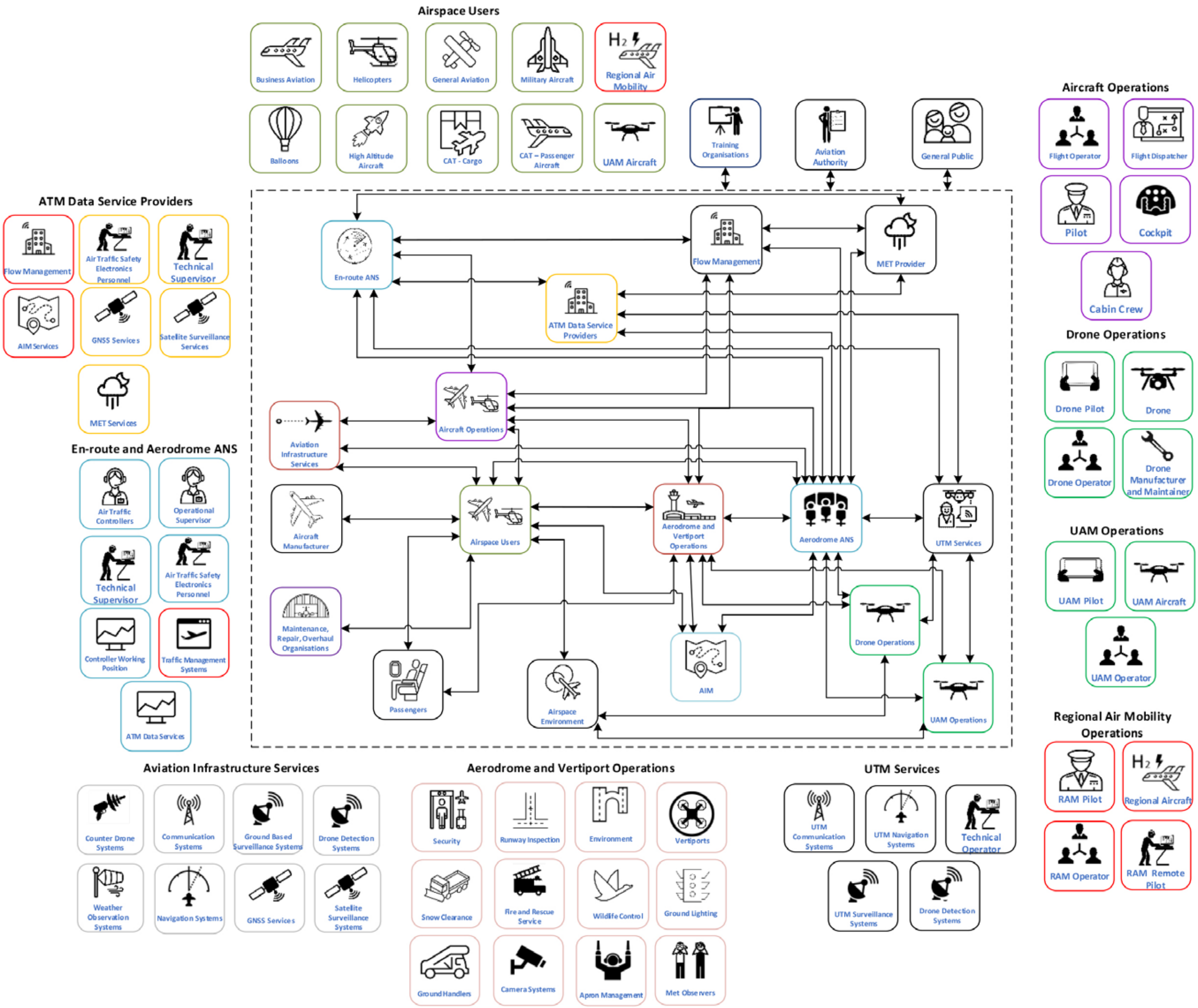
Designed for manned aircraft, providing the information and procedures designed and established for existing airspace users.

A unified approach to traffic management of UAS and manned aircraft.[6]

6. CAP1868 - A Unified Approach to the Introduction of UAS Traffic Management

Expanded view

Below, some of the main elements are expanded into groups which sit outside the dotted line to provide additional detail.



Long-term scenario

This diagram shows the expected changes to the aviation system in the long-term, i.e. up to approximately 15 years. The changes from the medium-term actor diagram are shown in red.

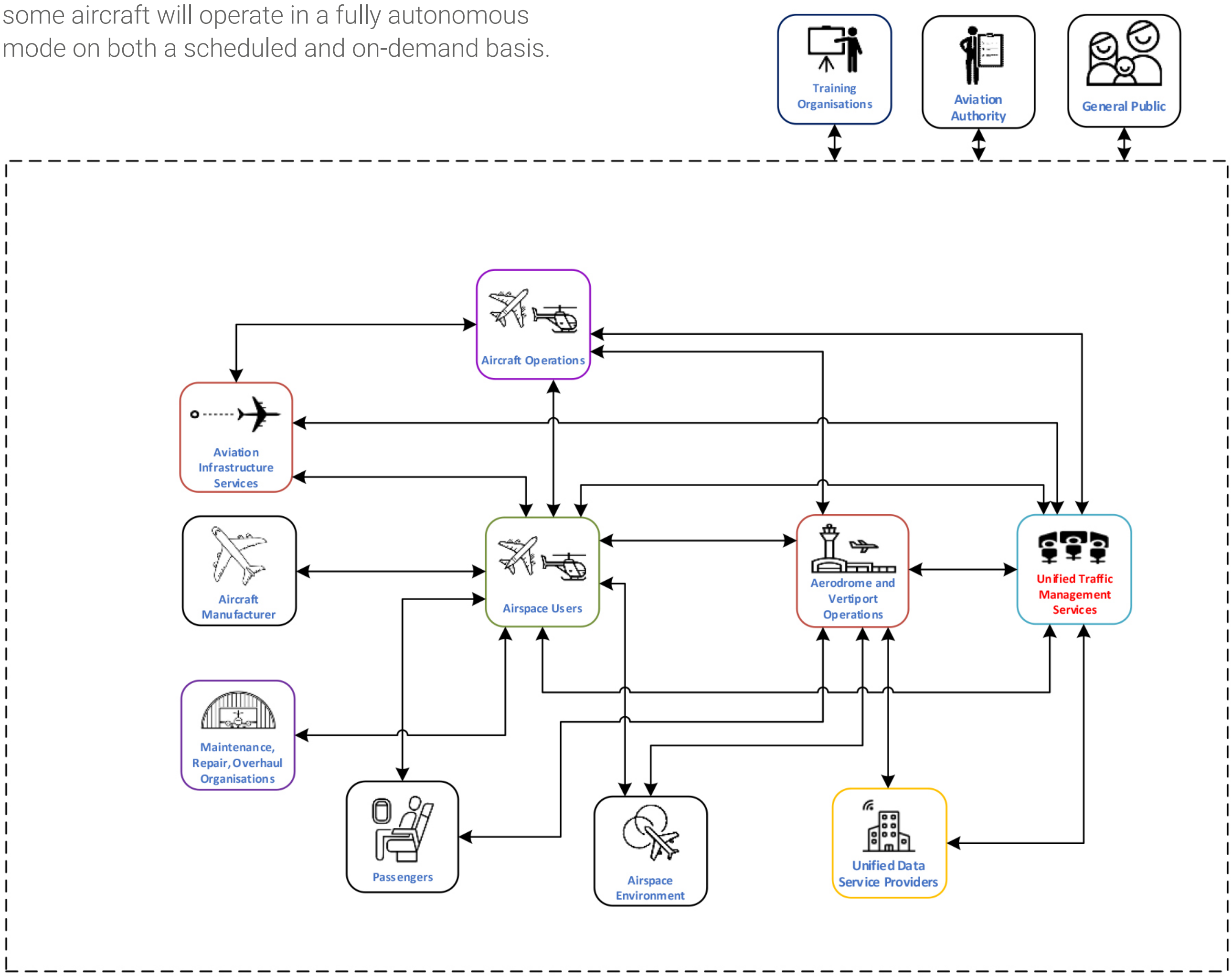
This scenario is characterised by widespread use of drones operating in an increasing variety of use-cases from provision of delivery services, inspection and monitoring, surveillance and broadcast, and robotic functions. The operational capabilities such as range, payload and complexity of function of these aircraft will increase over time increasing their potential deployment options. For example, there are drones in development today that will have a payload of 800kg and this is expected to increase over time well beyond 1,000kg.

The principal impact of increases in drone mass relate to the expected increase in severity of the consequences should a drone impact the ground or another airborne object. This will lead to a requirement to revisit the safety case for drone operations given the expected increase in potential risk. The expansion in freight aircraft is expected to include large, wide-body aircraft that are autonomously or remotely piloted as an option for reducing the crew costs of cargo flights. Numerous regionalised drone freight-hubs could emerge in industrially dense locations as well as adjacent to population centres.

UAM and RAM aircraft will be well-established and operate across a range of intra and inter-city use-cases serving the aerial transport needs of significant portions of society on a cost-effective, low carbon basis.

Advanced technology across both aircraft propulsion, guidance and control domains will be mature and some aircraft will operate in a fully autonomous mode on both a scheduled and on-demand basis.

Traffic management and other service providers will be fully integrated across both unmanned and manned aircraft domains forming a unified traffic management function.



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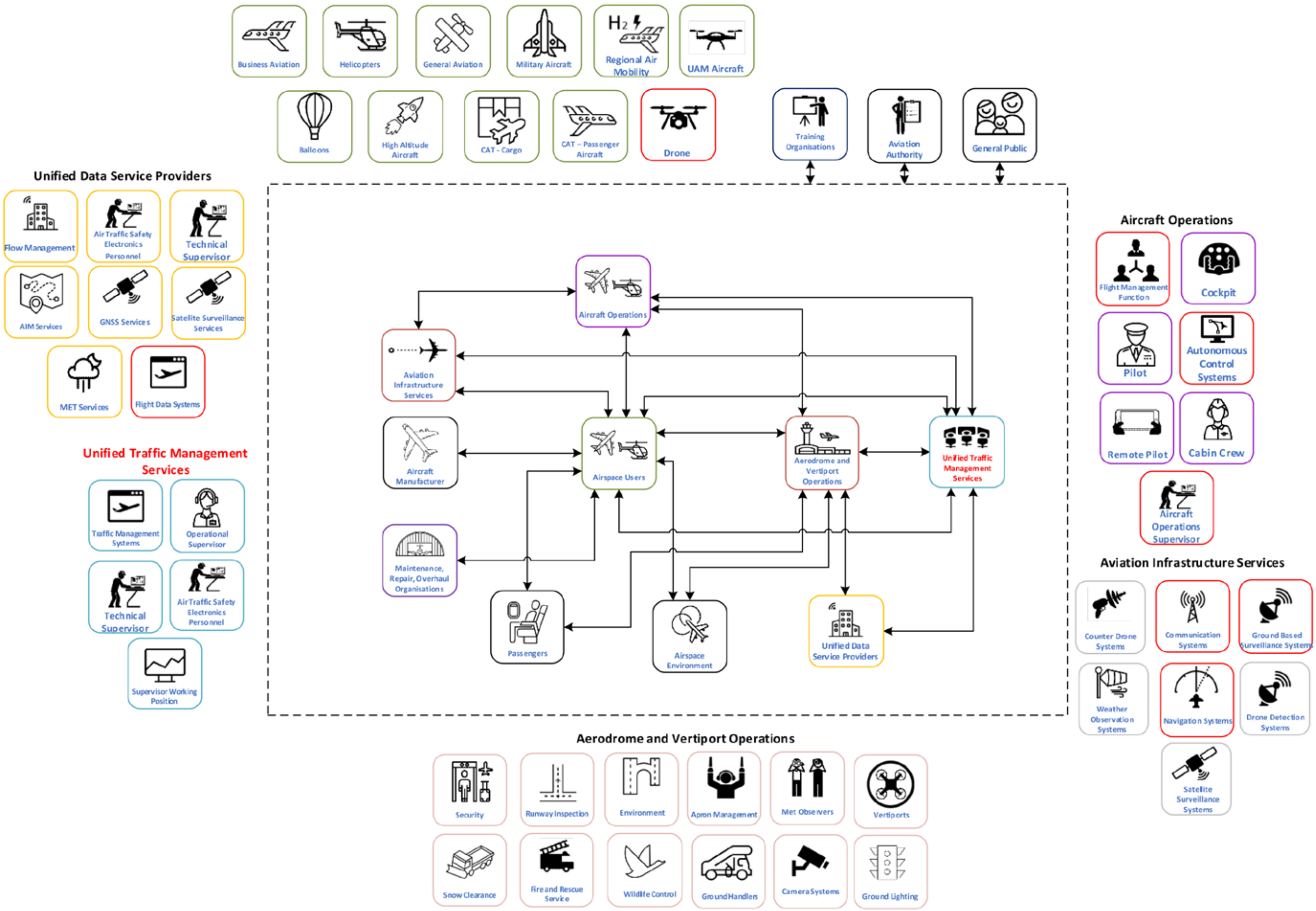


Synopsis

The regulatory and safety management framework will evolve to meet the demands of the new vehicles and operators with an integrated airspace structure, an integrated safety and other risk management framework and established safety assurance standards and processes for manufacturers, operators and service providers.

In the long-term, the main transition will be a move to a UnTMS that includes both ATM and UTM. This will represent the merging of service provision from the medium-term position to leave a less fragmented system. This change will include the continued evolution of the ATCO to a supervisor role, with the UnTMS providing separation and flow information to all airspace users. This change could also include the expansion of the Data Provision Services, with all flight data now being provided by Unified Data Service Providers (UnDSPs).

It is also noted that in this long-term vision, density of operations and variety of locations will significantly increase, with UAM aircraft being more commonplace in many large cities and other locations where the transport mode is value adding (e.g. remote locations with poor transport links). This will be reflected in an increase to the levels of infrastructure such as vertiports and maintenance facilities required in major cities as well as remote locations.

Drone services will become more extensive, with long range and/or long duration operations and higher weight category operations occurring. In addition, multi-drone operations (e.g. swarm operations) may become more common. Operations will occur across urban and remote environments.

For both drones and UAM, there could be a step change in the number of active air-operators/airspace users with many smaller new entrants with limited corporate history of aviation.

In this timeframe, climate change could become a significant factor in UK society. There could potentially be more extreme weather events causing higher temperature extremes and weather variability. Aircraft and supporting infrastructure will need to be qualified to operate in these extreme conditions to assure continued operations. Further, the importance of timely and accurate MET information will also increase under these conditions. Equally, resource usage constraints and maximising efficiency will increase in significance.

Use cases

Use Case 1 – Drones

Introduction

The rapid expansion of drones – in recent years has been enabled by technological developments (e.g. battery evolution) and new manufacturing processes (e.g. to reduce costs). We consider three sub-cases of drone operation in this section:

Drone delivery – e.g. for parcel or part delivery. There are also safety critical examples here such as blood or organ transfer between hospitals.

Drones for monitoring, surveying, inspection, surveillance and broadcast – e.g. for construction site surveys, filming, Wi-Fi broadcast.

Drones that perform a robotic function – e.g. for crop spraying, painting or repair of inaccessible items such as wind turbines. These drones will carry robotic systems to perform their function.

Short-term

Initially, many drones can be expected to be less than 20kg and operating at VLL with a mission distance of a few miles, perhaps up to tens of miles. However, in remote locations early applications may include larger drones providing cargo delivery (e.g. to oil rigs and islands). The operating characteristic parameters will expand over time with larger and longer-range drones becoming more widespread and operating at higher altitudes. Some novel, larger eVTOL cargo drones are under development that are due for entry into service in this scenario. In addition, drones with robotic functions will provide specialist services such as wind turbine cleaning and de-icing.

Some applications will have controlled take-off and landing areas (e.g. at hospitals), while others will be expected to have reasonably uncontrolled take-off and landing zones (e.g. parcel delivery). The use of uncontrolled take-off and landing zones may be limited in number in the short-term especially in densely populated urban environments.

Most of the drone services will be on-demand although some will operate on a regular or scheduled basis.

In the short-term, the generalised use of drones for BVLOS will still be in development. Initially BVLOS operations will be under controlled conditions (e.g. hospital to hospital or for infrastructure (e.g. railway) inspection purposes) where the take-off and landing points can be controlled and the route is pre-defined with low-risk exposure. BVLOS trials to carry hospital supplies have already taken place in 2020 during the COVID-19 crisis and also for deliveries to oil rigs.

As the use of drones in urban areas expands, there will be a corresponding increase in awareness of non-safety issues such as noise impacts and social acceptability, although they may be raised in combination with safety concerns.

Drones operating at VLL away from aerodromes and other restricted areas are out of range of most aviation infrastructure (e.g. radio, radar) and may be too small to carry transponders. They will operate on current Global Navigation Satellite Systems (GNSS) navigation services (multi-constellation) and, where they operate BVLOS, they will most likely use mobile telephony infrastructure for communication.

Medium-term

The main difference in the medium-term will likely be the expansion of BVLOS services into more generalised operations involving wider use of 'uncontrolled' take-off and landing zones. The increased use of 'uncontrolled' take-off and landing zones will be important for supporting an expansion of drone use-cases including emergency medical evacuation but will need to be supported by increased capabilities to ensure an uncontrolled zone is safe for use.

These operations may be enabled by improved vision systems on drones that can recognise and avoid obstacles in take-off and landing zones. These will be enabled by Artificial Intelligence (AI) vision systems. They may also assist conflict detection and resolution.

Drones may be deployed to repair and recover other drones. Drones may be used for extremely long missions both in time and distance. Equally, micro drones may be more widely used, individually and in swarms.

From a technology perspective, there will be a continued evolution of inertial navigation systems to allow continued navigation in the case of loss of GNSS or a degraded GNSS signal due to the "urban canyon" effect. Satellite communications may become enabled on relatively small drones (e.g. via the Starlink system).

7. Camcopter S-100 helicopter drone makes world-first oil rig deliver
8. Flylogix to trial UAV freight delivery for Isles of Scilly
9. Pipistrel begins to accept orders for Nuuva series of cargo eVTOL aircraft
10. Aerones develops de-icing and cleaning drone for wind turbines
11. NHS Drone Delivery Trial

Whilst the short-term use of drones may be identified from current Research and Development (R&D) activities, by the medium-term there could be whole new classes of drones in a new range of activities that we cannot foresee at this stage.

Long-term

In the long-term there will be an expansion in intelligent drones that will operate with little or no tactical input from the ground. This may include the ability to self-charge at charging points and plan and undertake autonomous missions with no direct human engagement.

Drones will increasingly interact with other aircraft such as UAM aircraft, which will also operate at low altitudes and in urban centres and increase in number. Drones will also develop additional applications which require access to airspace at all levels for potentially extended periods of time.

Use Case 2 – Urban air mobility

Introduction

UAM exists today in the form of helicopter transport and there are already a substantial number of helicopter movements. For example, between 2016 and 2019 annual helicopter movements in London ranged between 18,500 and 25,000[12]. Significant investment is being made in the UK and internationally in future UAM aircraft with VTOL capability. Current research and development are focused on eVTOL and Hybrid Electric VTOL aircraft.

Current UAM aircraft R&D is focussed on propeller or ducted fan for vertical lift with some designs also utilising wings for cruise flight. The flight phases of UAM aircraft will be:

- Take-off
- Transition (Climb)
- Cruise
- Transition (Descent)
- Landing

A key objective of many UAM aircraft currently in research and development is a significantly reduced noise footprint compared with current helicopter operations. The expected cost reductions in manufacturing and operation of eVTOL and hybrid aircraft and the expected reduced noise profile is the basis for predicted UAM industry growth.

A number of potential business cases for these aircraft have been identified including:

- Short intra-city air taxi
- Airport commute
- Longer distance taxi (up to 200 miles on a regional basis)
- Emergency services, including air ambulance, fire monitoring and fire fighting in high rise buildings, search and rescue operations

UAM services may be delivered through scheduled services or on an on-demand basis. UAM services may carry passengers or cargo or a combination of both. Most current research and development are focussed on aircraft which will carry between two and five passengers.

Ground based infrastructure for UAM operations will be required. Vertiports will provide take-off and landing facilities as well as parking facilities dedicated for UAM operations. Around aerodromes, vertiports may be integrated with other ground-based aviation infrastructure (for example airside facilities) or located close by but not integrated. Vertiports will have charging facilities for the aircraft; the patterns of aircraft movements and charging times will ensure sufficient energy for operations. Energy usage and recharging profiles will likely vary between UAM aircraft designs,

A trip may involve multiple UAM aircraft movements to re-position the vehicle before and/or after an intended flight.

Operation could be via large fleet operators similar to today's airlines or networks of private operators.

Short-term

In the short-term it is expected that trials of UAM aircraft, carrying passengers, will occur with the intention of providing assurance for commercial services. Following trials, initial services would commence and at least one manufacturer has targeted 2024[13] to start operational UAM services that will be operated with a pilot and four passengers.

Initial services are expected to have a PiC on board with the UAM aircraft operating under VFR in Visual Meteorological Conditions (VMC) and complying with current airspace and ATM requirements in a manner similar to other airspace users. Current conventional technology (e.g. ADS-B transponders, Very High Frequency (VHF) radio) applicable to other airspace users will be used.

12. *Data for helicopter operations within the London (Heathrow) and London City Control Zones (CTRs)*
13. *Vertical Aerospace Reveals 'VA-1X' Air Taxi, Targets 2024 for Commercial Operations*

Current helicopter routes may be used as well as other airspace in a manner similar to VFR operations by other airspace users. Existing aerodrome and heliport ground infrastructure may be used, but it is expected that vertiports, with some situated in dense urban environments, would be established and enter operation in the short-term to support early UAM services.

Medium-term

In the medium-term following initial services, an increase in the density of operations is expected, with more service providers operating numerous aircraft in the same airspace. To provide reliable services, flights will need to occur in Instrument Meteorological Conditions (IMC) which may require new regulations and procedures if current Instrument Flight Procedures (IFP) cannot be applied in a dense urban environment.

As well as requiring new flight rules, the current ATM procedures and airspace designs are likely to be insufficient to manage higher density operations.

New technology will likely be available in the medium-term including increased automation (e.g. sense and avoid), improved CNS (e.g. improved Navigational Performance). New technologies may lead to a change in role of various components of the aviation system including a move away from reliance on voice communications as the principal communication mechanism.

In the medium-term new technology may allow the trialling of remote pilot capability and the introduction of UnTM airspace concepts such as managed and unmanaged airspace with differing requirements on levels of aircraft equipage to operate in those airspace environments. The concept of simplified pilot skills may emerge whereby many current pilot functions are fully automated. This may reduce operating costs and enable pilot labour shortages to be overcome.

In the medium-term, it is likely that the peak in the range and variety of vehicle types will occur before potential consolidation.

The number of vertiport locations in cities will increase to support a greater volume and diversity of operations.

Long-term

In the long-term, there will likely be a further increase in the density of operations. A greater use of autonomy may see services provided with no PiC on board. However, some UAM services and other airspace users will still have a PiC on board. As such, a mix of autonomous, ground controlled and PiC on board operations will occur in the same airspace. Greater levels of integration of UAM operations with other airspace users will occur. Improvements in technology (e.g. CNS technology) will lead to higher navigation performance precision in flights and reductions in separation standards. Some airspace may become free-route with other airspace maintaining fixed routes. It is expected that overarching airspace system design and procedure specification will need oversight by an authority responsible for systems integration.

Use Case 3 – Regional air mobility

Introduction

RAM will likely be the next class of size up from UAM aircraft. Passenger numbers up to 100 will take city-city journeys to cover the distances between major population centres. Cargo will also use this mode. Similar to UAM, these aircraft will make use of new technologies to reduce the carbon footprint of the vehicle. These technologies may include pure/hybrid electric and hydrogen fuel cell forms of propulsion. The Airbus ZEROe[14] aircraft are powered by turbofan or turboprop engines using hydrogen as a fuel and are intended to be climate neutral zero-emission commercial aircraft.

Short-term

The first aircraft will be evolutions of current regional aircraft with similar characteristics. They will be treated in a similar way to conventional aircraft. The piloting of these aircraft will continue with the same trends as conventional aircraft, i.e. piloted but with increasing automation to support the pilot.

These aircraft will be treated as conventional aircraft, operating from airports and under conventional air traffic control rules. Initially, cargo aircraft may be more widely deployed than passenger ones.

Hybrid aircraft[15] will be able to achieve a longer range than all-electric aircraft and will be the first to emerge. Hydrogen-powered aircraft may also emerge powered by hydrogen fuel cells with airports developing new fuel storage and loading systems.

Medium-term

In this time frame, all electric-powered aircraft will start to be introduced. As eVTOL aircraft increase in size and range, urban take-off and landing zones

14. Airbus ZEROe Range of Hydrogen Powered Aircraft
15. Electric Aviation Group Unveils World's First Hybrid Electric 70+ Seater Aircraft

will also emerge for this class of aircraft in a similar manner to vertiports for UAM aircraft.

Hydrogen-powered aircraft may also become more widespread.

Autonomous aircraft will start to emerge for passenger travel. Several control combinations are possible:

- Single pilot in aircraft with autonomous fallback
- Single pilot in aircraft with remotely piloted fallback
- Remotely piloted aircraft with autonomous fallback
- Entirely autonomous aircraft

These autonomous and semi-autonomous aircraft will pose challenges as they are integrated with traditionally piloted aircraft. For example, the ATM system will need to treat autonomous aircraft as if they are manned and will communicate by voice and datalink. Even in abnormal or emergency situations such as responding to rapidly changing weather conditions or emergency avoiding instructions from the ATCO. The autonomous systems will need to be able to safely cope with the inconsistent sensor inputs and/or incorrect actions by external actors (e.g. an unsafe clearance given by mistake by an ATCO).

Long-term

In the long-term, flight performance of RAM aircraft may diverge significantly from conventional ones. For example, a blended wing[16] aircraft could have a different operating envelope to current aircraft.

The complexity of traffic management will increase as these aircraft mix on a broader basis with conventional aircraft - for example, when eVTOL aircraft rise vertically into complex airspace which is occupied by traditional jets travelling at high speed.

16. *Airbus reveals its blended wing aircraft demonstrator*

Safety management challenges of future flight

Complex systems in the aviation system

Aviation systems are becoming more complex (both technically and organisationally). Complex systems[17] have emergent behaviours based upon the interaction of the components of the system. Emergent behaviour cannot be reliably predicted simply from knowledge of the system components and their interactions. In addition, it can also be difficult to draw a boundary around a complex system and there are often interactions between systems and their environment which can lead to unexpected behaviour. This emergent behaviour can include safety-significant behaviours and outcomes. While it may be possible to determine the causes of these outcomes after a safety occurrence, predicting these outcomes becomes extremely challenging as system complexity increases. These issues are already apparent in the current aviation system and will become more prevalent as complexity increases.

Complex systems can lead to a variety of challenges for safety management including:

- Predicting and managing tipping points, where the system changes from one state to another potentially unsafe state from which it can be difficult to recover.
- Achieving resilience, where due to the potential for emergent behaviour, system operators and other stakeholders must have recovery mechanisms in place to manage failures, and other safety occurrences and reduce the likelihood and consequence of accidents.

Unless this is done, it will be hard to achieve trust, as the unexpected, emergent behaviour makes it more difficult for the system operators, users or regulators to have confidence or assurance of a system's ongoing safety performance.

Understanding the impact of complexity on the aviation system must be considered at all layers including:

- Governance – specifically regulatory and policy roles
- Management – organisational activities and processes that contribute to the safety performance of systems (e.g. safety culture and contracting)
- Task and Technical – the operation and use of systems

Within aviation, the complexity of systems is increasing rapidly. The number of organisations involved in FF, the pace of change and the technical complexity of the aviation system components are all increasing. A recent example is the impact of drones on ATM, as seen at Gatwick Airport in December 2018[18].

Integrated risk and safety managment

As documented in ICAO Annex 19, a key element of safety management is the consideration of risk. All safety management activities, but especially risk management, should be undertaken in an integrated manner. Integration ensures that activities are not undertaken in isolation (say within a single organisation) but in the context of other safety and risk management activities which may influence the outcome. These activities will often be in other organisations within the aviation system but may also extend beyond the aviation system, e.g. to infrastructure providers.

For the UK, (as is true for other States) there is no overarching safety case for aviation which presents an argument and evidence that all aviation operations are acceptably safe.

Within the current aviation system there is an implicit acceptance of different levels of safety for different operations. For example, for 2002-2011, the FAA estimated global airline accident rates of 0.4 fatal accidents per million hours flown. In the same period, for General Aviation (GA), the annual figure did not drop below 12. In the UK there is no data on the relative accident rate of different sectors, but we can expect that a similar distribution exists – GA may fly more in airspace without an ATC service to monitor their proximity to other traffic. Larger aircraft tend to have more systems such as TCAS (the traffic collision avoidance system) to provide a safety net.

Different Acceptable Level(s) of Safety Performance (ALoSP) are therefore applicable to different types of operation, and they may also be applicable to different phases of flight, although these are not necessarily documented and set as targets.

Given the lack of an overarching UK Aviation Safety Case, it is likely that the current safety management regime relies on a number of assumptions which may not be documented. The extent to which these assumptions impact the way safety is achieved is unknown. For FF, new types of aircraft and operations may break existing, implicit, assumptions which

17. *Safer Complex Systems: An Initial Framework, S Burton, J A McDermid OBE FREng, P Garnett, R Weaver, University of York, July 8, 2020*
18. *Gatwick Airport: Drones ground flights*

impact how an acceptable safety performance might be achieved. For example, the turn or acceleration performance of new types of aircraft may mean that they cannot be treated like existing aircraft from a collision risk perspective.

Managing safety across multiple stakeholders has potential benefits but is likely to be challenging. Currently, safety assessments are completed separately by ANSPs, airports and other aviation stakeholders. Instead, if an innovative, harmonised and integrated national framework was developed, as planned for within the UK Drone Strategy, the safety of the aviation system as a whole could be analysed and improved. This will become more important as more stakeholders enter the aviation system. The aim of this report is to take a first step towards overcoming the challenges of producing a safety case for FF that should realise some of these benefits.

Risk integration

There are many participants in the aviation system that together contribute toward safety outcomes. From a safety perspective, individual actors have significant ability to impact actors in other organisations which can either increase or reduce risk (i.e. provide external mitigation) beyond organisational boundaries. If not well managed, safety objectives within an organisation can be in contradiction with safety objectives in another organisation. For example, ATC instructions to an aircraft on approach may help maintain separation standards but could also be a contributing factor to an unstable approach for a pilot.

Approaches to consider risk across the aviation system, beyond organisational boundaries, are already an important element of effective risk management in aviation. For example, the EUROCONTROL Risk Analysis Tool[19] is a tool which aims to integrate consideration of risk beyond organisational boundaries. Further evidence of integrated risk management approaches is available from integrated Safety Management Systems (iSMS) such as the one in operation to manage risk at Schiphol airport[20]. The tool looks at the contribution of both the ATM and Airborne component to risk.

A key role for all aviation system participants is to understand how their services and operations impact, and are impacted by, other actors' aviation safety risk management. As new FF service providers join the aviation system it will be important for all participants to understand how their operations might impact aviation safety risks.

Risk management standardisation

A key element of achieving safety in aviation is the standardisation of practices which contribute to achieving safety outcomes. While standardisation can be beneficial it is inherently slow and can lead to slow change in what is required or allowed. A property which is common to drone and UAM development is the speed with which innovation occurs. A key challenge for FF will be to reconcile innovation speed with slow rate of change in standardisation and regulation.

Measurement and quantification of risk

New operations may need different ways of considering overarching level of risk acceptability - movements vs hours vs distance travelled. For example, UAM will have much higher number of movements over shorter distances.

The complexity of systems and the role of humans and organisations means that accurate predictive quantitative safety analysis is challenging and will become more challenging in the future[21].

Trade-offs with other key performance areas

ICAO identifies 11 Key Performance Areas (KPAs) within aviation (reference ICAO Doc 9854[22]). They are safety, security, environmental impact, cost effectiveness, capacity, flight efficiency, flexibility, predictability, access and equity, participation and collaboration, interoperability. While safety will always remain the highest priority in aviation, achieving an effective operation requires the need to balance or trade-off different KPAs. It is increasingly important to understand and manage other risks such as environmental impact, security and community/ social impact. How the management of these risks impact safety risk management and mechanisms to understand the relationship between these risks to allow explicit consideration of trade-offs will become progressively more important.

Role of the human and autonomy

Increasing autonomy and use of AI/pattern matching algorithms will change the role of the human in operations. Humans will oversee autonomous systems in their own organisation and also interact with external autonomous systems.

19. *Eurocontrol Risk Analysis Tool (RAT)*
20. *Safety in the Dutch Aviation Sector*
21. *A J Rae, R Alexander, J A McDermid, Fixing the cracks in the crystal ball: A maturity model for quantitative risk assessment. Reliability Engineering and System Safety, 2013, pp. 67-81. ISSN 0951-8320, http://dx.doi.org/10.1016/j.ress.2013.09.008i.*
22. *Global Air Traffic Management Operational Concept, ICAO Doc 9854, First Edition 2005*

As a system becomes more autonomous and complex it is harder for humans to maintain an understanding of all the actions in the system. Current flight-deck automatic systems return control to the pilot if an event occurs that the system cannot cope with, for example turbulence can cause the autopilot to disengage. It will not be possible to hand back control to a human in a complex, fast moving situation and expect that human to resolve it. Therefore, autonomous systems will need to be capable of maintaining control and safely resolving the situation under all failure modes - a major technical challenge.

Although all roles (e.g. pilot, ATCO) will benefit from increasing automation, it is important to note that a mixed equipage scenario will always exist, i.e. there are (manned) aircraft being delivered today that will be flying in 20+ years, operating in airspace with newly delivered unmanned/autonomous aircraft. Highly autonomous aircraft will still have to operate in parts of the world with a traditional traffic management system.

One solution is for autonomous aircraft to "fit around" the manned aircraft - i.e. they take account of them and avoid them. However, this will not result in an optimum airspace utilisation or traffic patterns and may even contribute to less safe operating environments – an example of the trade-offs mentioned above.

Supporting infrastructure

Physical and digital infrastructure will need to evolve to meet the FF operations. However, as described above, there will always be heterogeneous equipage situation with new aircraft using, 5G and satellite communications and older ones using radar and VHF datalink. One of the challenges (as it is today) is to allow all aircraft with significantly different technical capabilities to operate in the same airspace.

One solution applied today is airspace segregation (e.g. aircraft require a radio and transponder to enter controlled airspace) and this principle may also be applied in the future. However, a segregated airspace model will lead to sub-optimal solutions and as demand increases it may not remain practical. Access and equity obligations to ensure all aviation stakeholders can make use of airspace resources are expected to become more significant.

Detect and avoid systems will be key to enabling the co-existence of UAS and manned aircraft. This is an existing CAA programme of work.

One challenging area is air-to-air data interchange. Today, collision avoidance uses a standard air-air datalink but it is expensive and not suitable for very small aircraft. It may be necessary to assume that air-air direct communications are not always possible meaning that collision avoidance may need to be resolved by air-to-ground communications.

Cybersecurity will become increasingly important, especially when the system is entirely interconnected and controlled without manual intervention. As data provision services become more prevalent in the future ATM service architecture, the security of the data must be maintained. In the UK, the CAA is developing the "Cybersecurity oversight process for aviation" (CAP1753)[23] with the aim of creating a "proportionate and effective approach to cyber security oversight that enables aviation to manage their cyber security risks without compromising aviation safety, security or resilience."

Current technology assumptions will be challenged, e.g. current primary radar cannot always 'see' composite aircraft. So, the concept of primary radar as a backup in case Secondary Surveillance Radar (SSR) fails (which is its main use today) may not be possible. This would require existing safety cases in controlled airspace to be revisited.

A similar problem is that current standards are often written around particular technologies or specific operations. A simple example is airport control towers, where the procedures assume the controller is looking out of the window – this assumption was broken when remote towers were introduced and there was no window for the controller. Again, existing safety cases need to be revisited and new ones need to be developed that try to avoid locking procedures into specific technology solutions.

New technology will be introduced on shorter timescales than it was historically. Airworthiness standards will need to evolve rapidly, and aircraft certification may need to become more agile.

In general, FF will require safety management and regulation to become more agile whilst increasing effectiveness. The safety case approach proposed here, and the three scenarios for FF introduced earlier, are intended to provide a framework which enables agility whilst also promoting the coherence necessary to achieve integrated safety and risk management.

23. The Cyber Security Oversight Process for Aviation, CAP1753, UK Civil Aviation Authority, Issue 2 August 2020.

Bowtie safety analysis of the future aviation system

Introduction to the bowtie analysis

This section summarises the detailed safety analysis of the future aviation system across the three scenarios and use-cases. The approach used the bowtie modelling concept[24], a method adopted across many safety-critical industries to convey risk information to a variety of stakeholders. It is a flexible approach that can be applied at different levels of detail and does not require a detailed system or concept knowledge to bring value and insight. It is therefore ideal as a tool for understanding risk at a conceptual level for programmes early in the development lifecycle hence is well suited to the FF programme.

The bowtie approach hinges on a central hazard/top-event combination where the top event represents a loss of control event arising from the hazard. In an aviation context, a hazard may simply be the operation of an aircraft with the top event representing some deviation from normal in-flight parameters, e.g. failure to follow a cleared path through the airspace. The approach also recognises that there are causal chains linking causes (known as threats) to each top event and that the occurrence of each top event can lead to a range of different consequences. Controls that act to reduce the frequency of either the top event (preventative) or the frequency of a consequence (recovery) can also be represented in the diagram. In a safety context, consequences must lead directly or indirectly to a harmful effect (e.g. injuries or fatalities). The risk associated with each consequence is then a function of the severity and frequency and can be plotted on a risk classification scheme to determine acceptability.

Application of the bowtie to future flight

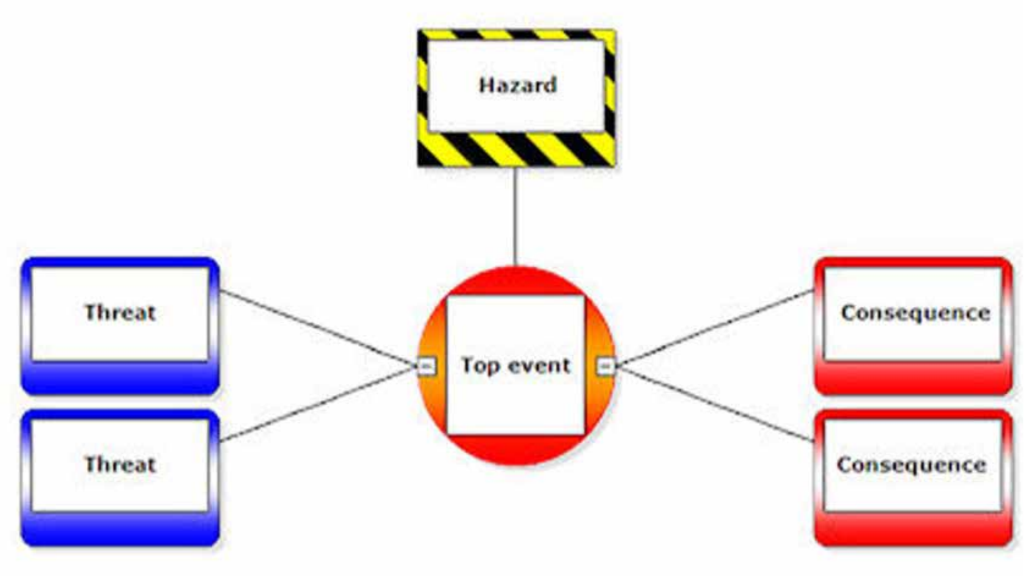
The bowtie approach has been applied to FF to achieve the following objectives:

- Understand the impact of FF on the risk of existing UK aviation operations
- Understand the new hazards and risks associated with FF

The scope of the bowtie analysis is focused on safety consequences although other concerns (e.g. environmental) are important and should be considered in the broader FF programme. Furthermore, the bowtie concept can be applied at varying levels of detail from analysing a single hazard within a system or component to a much higher level, where the objective is to understand, at an overall system level, the key hazards, the key threats and key controls. In the FF context, the approach has been applied at a strategic level to understand any new potential hazards and controls that may be needed to reduce the associated risk to acceptable levels.

The expected output of this analysis is a greater understanding of the risks, and causes of risks, associated with FF operations across all scenarios and use-cases with a particular focus on the new and modified controls that will be needed to manage those risks. The refinement, specification and implementation of these controls into the future aviation system will then be a key objective moving forward for the programme.

It is clear that both the introduction of new aircraft and expansion in use of existing forms of aircraft



The Bowtie diagram format.

24. CAA Introduction to Bowtie.

(drones) covered under the use-cases has the potential to affect the risk associated with existing UK aviation operations. The extent of this impact will depend on the rate of expansion (i.e. volume of new aircraft) and the diversity of missions and therefore airspace types that they occupy. The approach to regulation and certification of these new aircraft types together with changes to airspace structures and other supporting infrastructure will also influence the risk impact but, even with these uncertainties, it is still possible to make informed judgements about the potential risk impact when compared to an existing risk baseline.

For existing UK aviation operations, this risk baseline is provided partially by the Significant Seven series of bowtie models. Although the scope of these models is limited to Commercial Air Transport (CAT) aircraft, it provides a useful baseline from which to draw some initial conclusions about the risk impact from introduction of new aircraft and expansion in the use of drones. The analysis of the impact is limited to the short-term scenarios as the long-term scenario assumes fully integrated operations and therefore the distinction between existing operations and new operations will no longer be present. This means that there will be a "future" equivalent of the Significant Seven that aims to address all aircraft operations in the long-term vision of the future aviation system.

Example bowtie

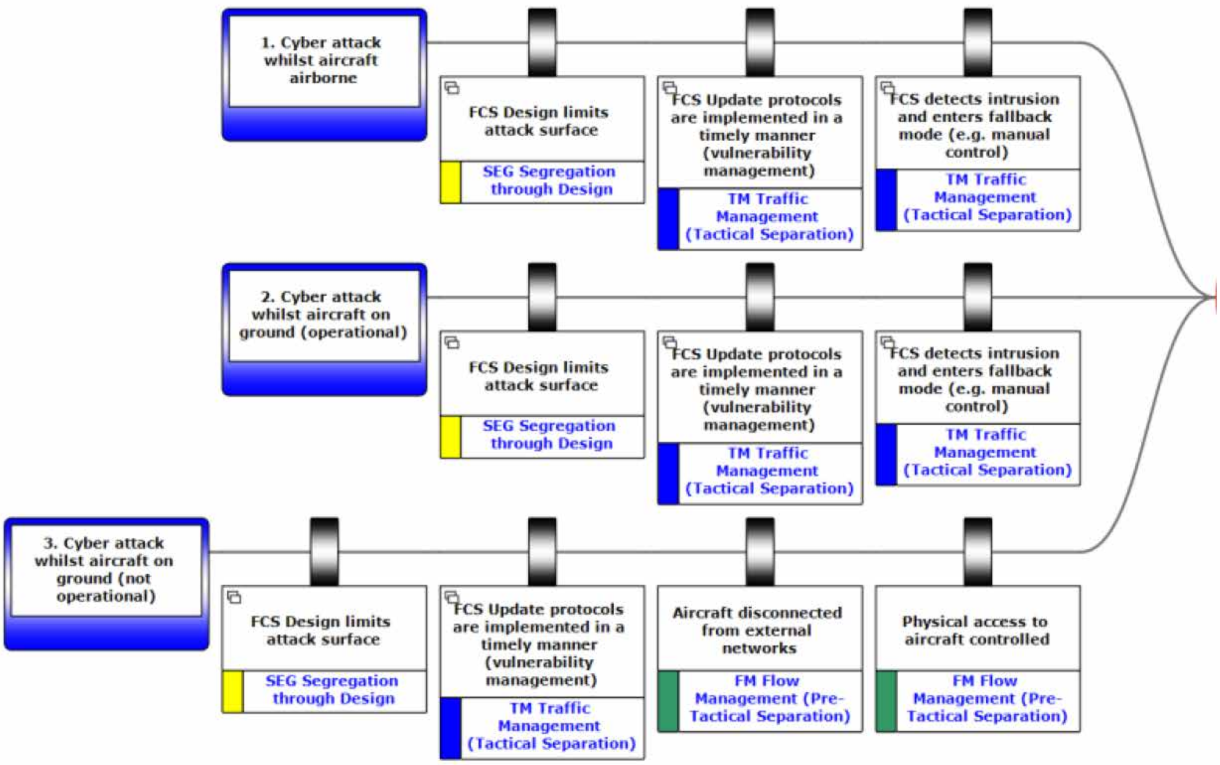
An example bowtie model created as part of this study is shown below including a number of the strategic defences that have been highlighted.

Summary of bowtie analysis results

Impact of existing hazards

The changes to the risk associated with existing hazards relate to the increased volume of drones operating in the airspace particularly at lower altitudes and around aerodromes. This could manifest itself in an increased frequency of interference or disturbance to existing aviation (CAT aircraft) which could result in an increased frequency of occurrence to the hazards. Increases in hazard frequency would then result in increases in consequence frequency although there are a number of hazards which feature additional recovery controls which would mitigate that increase in consequence frequency.

It is clear that existing procedures and approvals related to drone operations must account for increased drone activity particularly around aerodromes where CAT aircraft are more vulnerable to drone strikes and have fewer opportunities to take avoiding action. Drone pilots/operators and flight crew must maintain situational awareness (SA) to ensure separation particularly as the ability of ATC to detect small drones and inform flight crew will be limited with current surveillance technology. There may be some additional controls relating to aircraft design that may make them more resistant to drone-strikes but this is expected to be less effective as drones become larger and heavier in the future. Deployment of counter-drone systems may also reduce risk but there is some uncertainty over the effectiveness of these systems particularly as drones that have been disabled in flight may lead to other



safety consequences particularly to individuals on the ground.

It will be important to further validate the impact of drones on existing CAT aircraft operations and attempt to understand, from operational experience, the risk impact. This is a key input to the decision-making process to determine whether the existing controls are sufficient and whether new controls, or improvements to the effectiveness of existing control are required.

New hazards

A limited set of new hazards has been proposed using the Significant Seven as a basis. These have been adapted for drone operations and recognise that some of the traditional strategic defences (e.g. ATM based flow management or separation management) may not be effective or as effective in a drone context.

The new hazards are:

- Loss of Control - Drone Operations (Human Performance)
- Loss of Control - Drone Operations (Adverse Environmental Conditions)
- Loss of Control - Drone experiencing technical or loading failures
- CFIT - Drone operation in uncontrolled airspace
- CFIT - Drone operation in controlled airspace

The risks associated with these new hazards are uncertain at this stage, but the profile will be significantly different from the risk profile associated with CAT aircraft. This is due to many factors, but the severity of drone based mid-air collisions and ground collisions, and the frequency of those consequences, will be very different to CAT aircraft.

Bowtie analysis of new hazards

The threats and controls for the loss of control hazards are similar to CAT aircraft but there are some significant changes related to the expected effectiveness of controls. These include the following key areas:

Drone Pilot/Operator - the ability to detect and correct deviations from planned flight paths based on SA will be dependent on the level of information available to the remote pilot and the training/competency of the pilot to react to that information. The level of SA will be dependent on whether the operation is visual or beyond visual and the drone's capability to sense obstacles, adverse weather and other aircraft. The status of the drone's systems and its ability to communicate that reliably to the pilot/operator is also important in allowing the pilot/operator to take an appropriate course of action.

Drone Platform - the performance characteristics of the drone will be key in determining its ability to withstand adverse weather and respond in a timely manner to control inputs whether in normal or emergency situations. Integrity of drone systems and the level of redundancy/diversity in propulsion, energy storage and control systems will also be critical.

ATM / ATC Input - the reduced role of air traffic management/control will require drone pilot/operators to take greater responsibility for self-separation from other drones and obstacles. Although restrictions on drone use particularly around aerodromes will be enforced, unauthorised entry into controlled airspace and the ability of ATC to detect and resolve those occurrences will be limited based on current communications and surveillance technology.

As with the changes to the existing Significant Seven bowties, it will be important to validate the new hazards associated with drone operations and confirm that the key risks are understood and controls are sufficient to manage the risk. The emergence of BVLOS operations will be fundamental to validating the understanding of risks and sufficiency of controls given this mode of operation is likely to present significant safety and operational issues that challenge traditional forms of mitigation associated with visual operations.

Impact of future flight on future UK aviation operations

This section focuses on the long-term scenario for the UK aviation system and seeks to identify the key hazards that are most relevant to the use-cases for future operations including those that do not exist in the current aviation system.

The approach is focused at a strategic level and, for each hazard, identifies the key controls from a preventive and mitigative perspective that can reduce the risk associated with the consequences of each hazard. It is not intended to be an exhaustive or detailed exercise that identifies all potential controls but focuses on identifying the controls that comprise the following strategic defences against aviation risk:

- Design (airspace, aircraft, system) features providing inherent protection against the hazard and/or consequences
- Strategic controls such as flow management as provided by Air Traffic Management

- Tactical controls such as separation provided by Air Traffic Control
- Pilot see-and-avoid (more generically known as detect and avoid in the future)
- ACAS (an automated collision avoidance system)
- Emergency response planning

From the analysis, a number of requirements were derived that relate to the technical capabilities of the systems and elements needed to deliver the functions associated with each control.

These requirements provide detail on the capabilities that will need to be developed and implemented in the future aviation system.

Recommendations

Recommendation 6.1 - It is recommended that a more detailed review is conducted into the risks attached to cyber related attacks on aircraft flight control systems to understand the potential risks and inform system design activities.

Recommendation 6.2 - It is recommended that vulnerability of new aircraft types to loading errors is investigated further and appropriate automated and procedure-based mitigation developed as necessary.

Recommendation 6.3 - It is recommended that terrain avoidance systems are specified to operate safely and effectively in an (urban) obstacle-rich environment.

Recommendation 6.4 - It is recommended that the threat lines associated with a sample of bowtie diagrams are analysed in more detail to understand the dependencies between controls whether those are human or machine based. The reliance on shared systems (e.g. electrical power from the same source) should also be investigated as part of this activity.

A number of functional requirements were also derived from the bowtie analysis to be considered in the design, implementation and operation of the key technical elements of the future aviation system. These requirements related to:

- Airspace Design
- Traffic Management System
- Flight Control System
- CNS Technology
- Aircraft Design
- Aircraft Collision and Avoidance Systems

Complex systems analysis of the future aviation system

Safer complex systems framework

Introduction

In this section we present the results of an analysis of the impact of complex systems in the future aviation system and the associated additional controls that may be needed to mitigate negative impacts. Issues regarding integrated risk and safety analysis and autonomy are integrated into this analysis.

Engineering X, an international collaboration founded by the Royal Academy of Engineering and Lloyd's Register Foundation (LRF), has launched a £5 million, five-year programme, Safer Complex Systems, to enhance safety and resilience of complex infrastructure systems globally[1]. The objectives of the programme are:

Enhanced understanding and capacity of key stakeholders to deal with complexity and to safely design, manage and regulate complex systems globally.

To build and convene a diverse, global complex systems community to improve collaboration and increase knowledge sharing across sectors, disciplines and international boundaries.

Improved pathways for application of theory into practice to practically address issues that make complex systems unsafe.

Engineering X commissioned the University of York to undertake an initial review of safety in the design, management and governance of complex systems. The aim of the review was to develop conceptual clarity; identify methods for the design, management and governance of complex systems; and outline emerging challenges and opportunities with regard to the safety of complex systems. The study included findings from stakeholder workshops (including a large technical advisory group), informal meetings, and an online questionnaire. A framework was developed for the design, management and governance of complex systems.

Description of safer complex system framework

As stated in the study report, "Ensuring the safety of increasingly complex systems is challenging. In particular, unacceptable levels of risk will occur if the complexity of the systems and their operating environments outpace our ability to engineer, operate and govern such systems." The study considers the impact of complex systems across three layers:

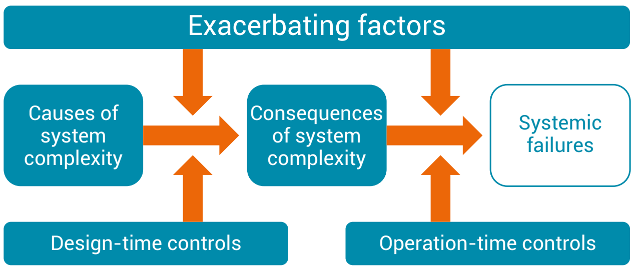
Governance – This layer consists of incentives and requirements for organisations to adhere to best practice through direct regulation, so-called soft law approaches or a consensus in the form of national and international standards. In formulating these standards and regulations, governments and authorities represent societal expectations on the acceptable level of residual risk that is to be associated with the systems.

Management – This layer coordinates tasks involved in the design, operation and maintenance of the systems, enabling risk management and informed design trade-offs across corporate boundaries, control over intellectual property and liability, management of supply chain dynamics and sustaining long-term institutional knowledge for long-lived and evolving systems.

Task and technical – This layer covers the technical design and safety analysis process that allows systems to be deployed at an acceptable level of risk, then actively monitored to ensure deviations between what was predicted and what is actually happening so that these gaps can be identified and rectified. This layer includes not only the technological components but also the tasks performed by the users, operators and stakeholders within a sociotechnical context. In some cases, users may be unwilling or unknowing participants in the system who are nevertheless impacted by risk.

Safer complex systems framework elements

The framework has six major elements:



The framework elements are defined as follows, starting with the middle causal flow and ending with the exacerbating factors:

- **Causes of systems complexity** – factors at the governance, management and task and technical levels that engender complexity in systems, building on the concepts from complex systems theory, for example rapid technological change.

25. www.raeng.org.uk/global/international-partnerships/engineering-x/safer-complex-systems.

- **Consequences of systems complexity** – manifestations of complexity at the governance, management and task and technical levels, which can lead to unsafe behaviour if not properly managed, such as unintentional and unrecognised risk transference between stakeholders.
- **Systemic failures** – failures relating to the whole system, rather than a particular part, that impact the safety of some or all of the stakeholders in a system, for example inadequate regulatory control.
- **Design-time controls** – approaches that can be applied at the governance, management and task and technical levels to reduce the causes of complexity and/or to reduce the likelihood that the consequences will occur, such as inclusive design.
- **Operation-time controls** – approaches that can be applied at the governance, management and task and technical levels to reduce the likelihood of the consequences of complexity giving rise to systemic failures or reducing the risk associated with such failures, for example contingency planning.
- **Exacerbating factors** — things that make the management of complexity more difficult perhaps inhibiting both design time and operational management strategies. This might be conflicting legislative requirements on the system as a whole or between system elements.

The purpose of the Safer Complex Systems Framework Future Flight analysis was to apply the Safer Complex Systems Framework to the FFC to gain insight into the potential considerations for the use of complex systems in FF. The analysis supports the development of a Future Flight Aviation Safety Framework.

Application of the framework to future light

The Safer Complex Systems Framework Future Flight analysis identified the key constituent factors within each element of the framework that are relevant to the FFC. Priority was placed on design-time controls and operation-time controls as these can be used as a basis to identify the key recommendations and activities which FFC stakeholders should consider in order to manage the safety challenges of complex systems. Recommendations and activities are focussed on actions that could commence in the short-term. As future horizons are reached, other recommendations and activities are expected to be identified following further analysis.

The analysis included:

- A description based upon that within the Safer Complex System Framework Report with minor edits to improve comprehensibility in the aviation context
- An analysis of the relevance to FF
- Identification as to whether the controls are a priority consideration for FF
- The key FF stakeholders to which the control is relevant
- Key recommendations and activities that should be implemented to assist in ensuring the effectiveness of the control for FF

Summary of analysis results

The following results have been drawn from the analysis. Recommendations have been developed for a range of FF Stakeholder Groups. These groups are:

- Governance Organisations (Policy and Regulation)
- Standards/Professional Bodies, Industry Organisations (current aviation and other industries on which aviation depends – e.g. communications industry organisations)
- Supporting Infrastructure Providers
- New Entrants
- New Technology and FF Operators
- Current Aviation Industry

In addition, a research agenda has been identified where further work is needed to determine the applicability of certain Safer Complex Systems Controls to FF.

The recommendations and activities may be relevant to other stakeholder groups including:

- Urban Infrastructure Providers and Operators
- Aviation Financing and Insurances organisations
- Adjacent service providers

It should be noted that the recommendations below present a significant and challenging work programme if they are to be addressed. The FF use cases in this project have been described across the time horizons discussed in the short-, medium- and long-term scenarios. The challenges of complex systems described in the analysis are expanded to extend out to the long-term time horizon. As such, it is expected that addressing the impacts of complexity of safety in aviation will be a continual activity into the future. Some impacts of complex systems are likely to occur in the short-term and it will be important to commence action to address these quickly. To aid this process, initial activities which are identified as the first step towards achieving the recommendations have also been identified.

Governance organisations (policy and regulation)

Standards/Regulation/Law

Recommendations:

- Determine the extent to which current standards can be applied or adapted to new FF operations using the principles of outcome-based standards supported by Acceptable Means of Compliance (AMCs).
- Develop appropriate standards for FF operations where current standards cannot be adapted using the principles of outcome-based standards supported by AMCs. For example, aircraft certification processes will need to potentially support a higher volume of certification resulting from a large number of new entrants and the likely shorter service lifecycle of novel air vehicles, including major through-life upgrades.
- Review how tort/common law are impacting other industries adopting autonomous systems and assess the implications to FF.

Engagement

Recommendations:

- Ensure appropriate diversity and inclusion in Policy, Regulation and FF concept and system development.
- Ensure regulators have a practical means to engage with FF industry development during advancement of technology and services.
- Ensure that a mechanism exists for the active management of negative consequences of regulatory engagement in development.

Safety performance

Recommendations:

- Ensure early proactive incident and accident analysis of FF operations to ensure lessons can be learnt across the FF industry.
- Ensure appropriate Target Levels of Safety are defined, achieved and reviewed for Drones, UAM and RAM.
- Ensure an enhanced operational monitoring approach is in place for FF operations.
- Ensure active alerting practices are enhanced to manage the high tempo and reduced human control use cases of FF operations.

Recommendations for other organisations

Standards/Professional bodies, industry organisations

Recommendations:

- Identify key areas where industry community guidelines would support safety assurance of FF and produce a roadmap for their development.
- Establish means for industry-wide learning from FF complex systems incidents and accidents, with a particular focus on smaller FF participants.
- In light of global events in aviation and other safety critical industries, review the effectiveness of learning from experience at Governance and Management Layers in UK Aviation.

Supporting infrastructure providers

Recommendations:

- Ensure supporting infrastructure providers publish Concepts of Operation (CONOPS) to enable FF technology development.
- Ensure supporting infrastructure has a roadmap for Publicly Available Specification (PAS) development which aligns with FF technology development and associated PASs.
- Ensure future traffic management provider roles are defined and their role in system integration is strategically planned.

New entrants

Recommendations:

- Ensure FF new entrants understand and adopt the mature aviation industry safety management practice in: principles of High Reliability Organisations[1], Safety Management Systems, risk and hazard analysis, active risk management, monitoring and analysis, incident and accident analysis, learning from experience as part of an effective safety culture (including Accident investigations), change management, CONOPS development, safety/assurance cases (design and operational risk management), independent assessment, competency management (for operations, development and safety), organisational resilience, contingency planning and contingency rehearsals.

New Technology Developer and Future Flight Operators

Organisations developing new technology and/or operating FF systems and services should ensure:

- new FF technology development has strong engagement with aviation and urban industry stakeholders and is cognisant of the future landscape.
- appropriate stakeholder diversity and inclusion in FF concept and system development.
- incremental delivery roadmaps are used to strategically work towards radical change in FF operations.
- new technology and systems apply design for assurance principles.
- new technology and systems provide effective diversity and redundancy in delivery of products/services compared to the current aviation system.
- the impact of autonomy is reflected in safety assurance requirements across the supply chain/network.
- competency management practices evolve as the role of Autonomy increases.
- FF participants adapt their SMS to incorporate FF challenges including new concepts, new stakeholders, integrated risk management and complex systems.
- aviation safety change management practices are adapted to manage the dynamic and complex nature of FF change.
- practices are in place to manage safety across the supply chain/network.
- all FF participants have mature processes for cyber resilience (design & operation).

Current aviation industry

Recommendations:

- Ensure that all aviation system participants consider the changing aviation system landscape and how FF operations will impact the safety of their operations.
- Ensure aviation safety change management practices are adapted to manage the dynamic and complex nature of FF change.
- Assess how existing diversity and redundancy in systems is impacted by new FF systems and operations, including the potential for cyber threats to introduce common mode safety-relevant failures.

Research agenda

In addition to the recommendations and activities identified from the main report, certain controls from the Safer Complex Systems Framework require further research to understand their applicability and relevance to FF. A research agenda has been identified for these areas with the following areas highlighted as most relevant:

- The application of risk and hazard analysis techniques for complex systems and their adoption in aviation
- The role of the following controls in safety assurance for autonomous FF operations
  - Simulation and modelling
  - Digital twins
  - Dynamic risk management
  - Self-monitoring
  - Scenario Based testing
- The impact of autonomy on:
  - Maintaining appropriate levels of human competency in FF operations
  - System adaptation processes
  - Human oversight
- The role of future traffic management systems in providing run-time assurance (similar to current ATC services)
- The importance of task analysis in supporting the transition of FF to greater use of autonomy

Recommendation 7.1 – A joint academic and industry research program should be established to advance understanding in these areas.

An initial safety framework for future flight

Introduction

This report has described the key contextual components for an initial safety framework for FF, which are:

- A description of the current UK Aviation System focussed on elements relevant to FF.
- A description of the future UK Aviation System which shows how the roles of different stakeholders will change over time as new FF operations are implemented.
- A description of the Use Cases for FF operations described over different time horizons.
- A description of the key safety management challenges of FF.

Based upon this contextual description an analysis has been undertaken to consider the safety impact of FF. This analysis has focussed on:

- The impact on hazards, threats and controls of FF Use Cases in the current and future aviation system using the bowtie approach.
- Key safety challenges relating to FF.

In this section we describe how these elements can be brought together to develop an initial safety framework for FF. This framework is particularly focussed on the top layers of a safety case which sets out the safety argument strategy for demonstrating the overarching goal has been met with respect to FF. The framework is outlined below using GSN.

Given this is the first iteration of this framework, many of the goals outlined are not yet satisfied with appropriate evidence. The aim of presenting the framework at this stage is to indicate what activities are required to achieve the intent of the overarching safety case. This is similar in nature to the development of an initial safety argument during a safety change management activity, which then can be used to inform safety planning.

The framework below is not intended to be definitive or represent something that industry or the regulator is committed to, but a means to identify principal activities and tasks required to demonstrate that the future aviation system is tolerably safe. These activities and tasks can then be used to build a roadmap of activities/tasks that should be progressed to develop the FF industry safety case in a collaborative and practical manner.

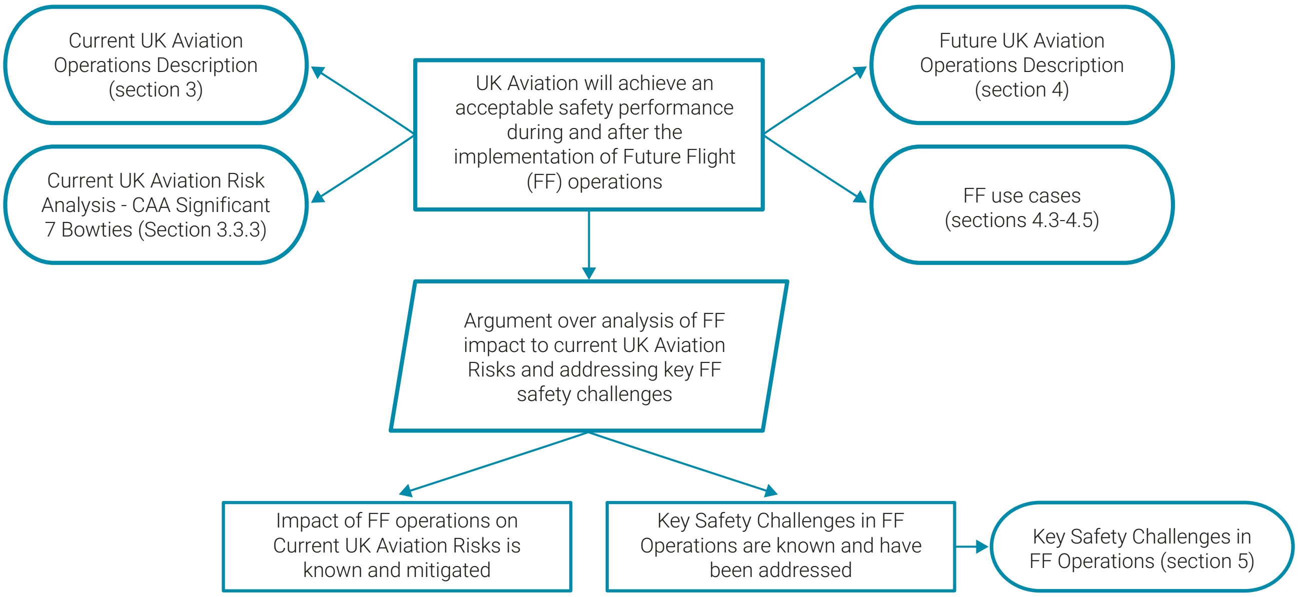
As the UK aviation industry evolves, this safety framework will need to evolve and be developed with evidence produced to satisfy the claims made.

Top-level argument

The overarching goal of the framework is to assure that:

> *UK Aviation will achieve an acceptable safety performance during and after the implementation of Future Flight (FF) operations.*

The top-level argument to achieve this claim is described below. Following the approach taken in this project, the argument is divided over the mitigation of the impact of FF on current UK aviation safety risks and the management of key safety challenges related to FF. The lower-level claims in the argument above are broken down further in the following sections in line with the approach taken in this project.



Impact of future flight on UK aviation safety risks

Understanding the impact of FF operations and mitigating that impact is key to ensuring acceptably safe outcomes with respect to FF integration with UK aviation operations. The argument below presents an initial argument structure to achieve this goal. Note, not all goals are fully developed in the argument structure below. Those which have not been expanded are shown with a diamond underneath the goal.

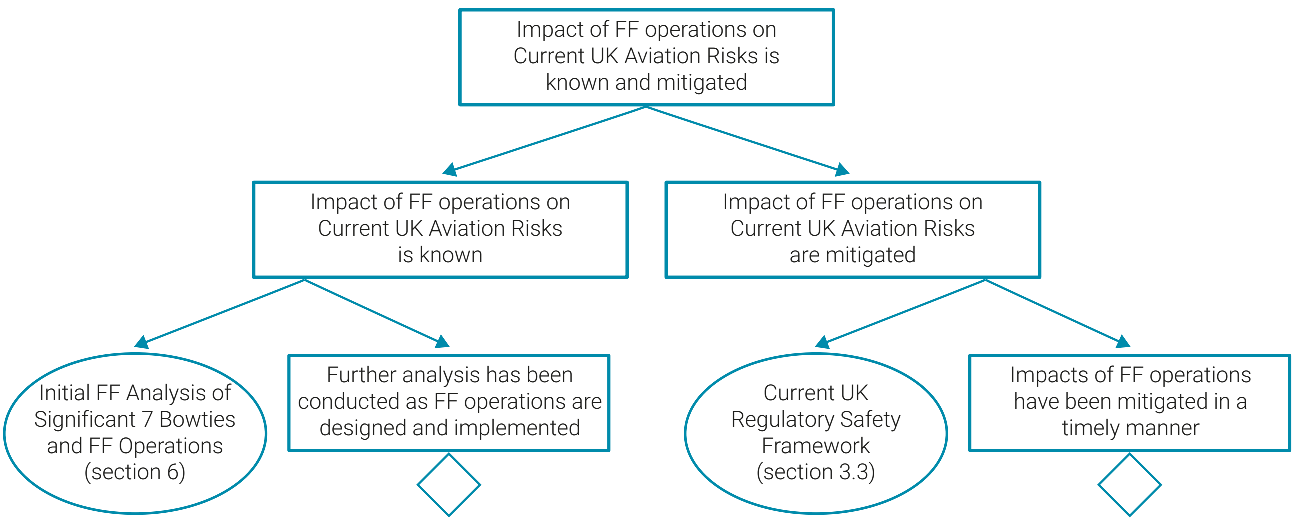
This project has conducted an initial analysis of the impact of FF operations across the both the short-term current UK aviation safety risk profile and the long-term future UK aviation safety risk profile, based upon the expected changes to the aviation system. The analysis will require further development as knowledge increases, especially as FF operations are designed and implemented.

It will be critical to mitigate the known impacts of FF on hazards, threats and controls at a whole-of-aviation-system level and this goal will need to be developed further as FF operations are designed and implemented. Mitigations should be considered across the governance, management and task/technical layers of the UK aviation system as discussed in the complex systems analysis. It is unlikely that any individual layer or stakeholder group (e.g. regulators or FF systems developers) will be able to fully mitigate UK system-wide aviation safety risks that are likely to occur over the long-term. Holistic and coordinated consideration by UK aviation system stakeholders is needed to achieve effective mitigation.

Mitigation will need to address both transitional risks as well as longer term steady-state operational risks. At an aviation system-wide level, transitional risks may be more challenging, for example where there is a mix of operational performance capabilities and levels of autonomy. Determining the exposure length of these transitional risks as the aviation system moves from the short-term concepts to the long-term concepts should be explicitly considered and determined. The challenges of a quicker transition to new operating concepts must be weighed up against the transitional risks of a more complex operating environment.

To be able to conduct further analysis throughout the short-, medium- and long-term, it is recommended that a UK Aviation Risk Baseline is maintained using an appropriate methodology such as the bowtie approach. The benefit of using the bowtie approach is that it enables a wide range of stakeholders to engage in discussions about risk and bring together a variety of types of threats and controls. The technique can be applied in varying levels of detail, including up to the aviation system level, as has been done in this project. As shown by this project, maintaining a risk baseline made up of both current risks and the future risk landscape will help inform understanding of the risk impact of strategic changes to the UK aviation system. These strategic changes should be considered holistically in addition to individual, specific changes that will occur through the implementation of specific FF operations.

In addition, a UK aviation system risk baseline in this format provides a means of identifying safety performance monitoring measures and can also be used as an input for safety occurrence management and investigations.



Mitigation of known FF safety challenges

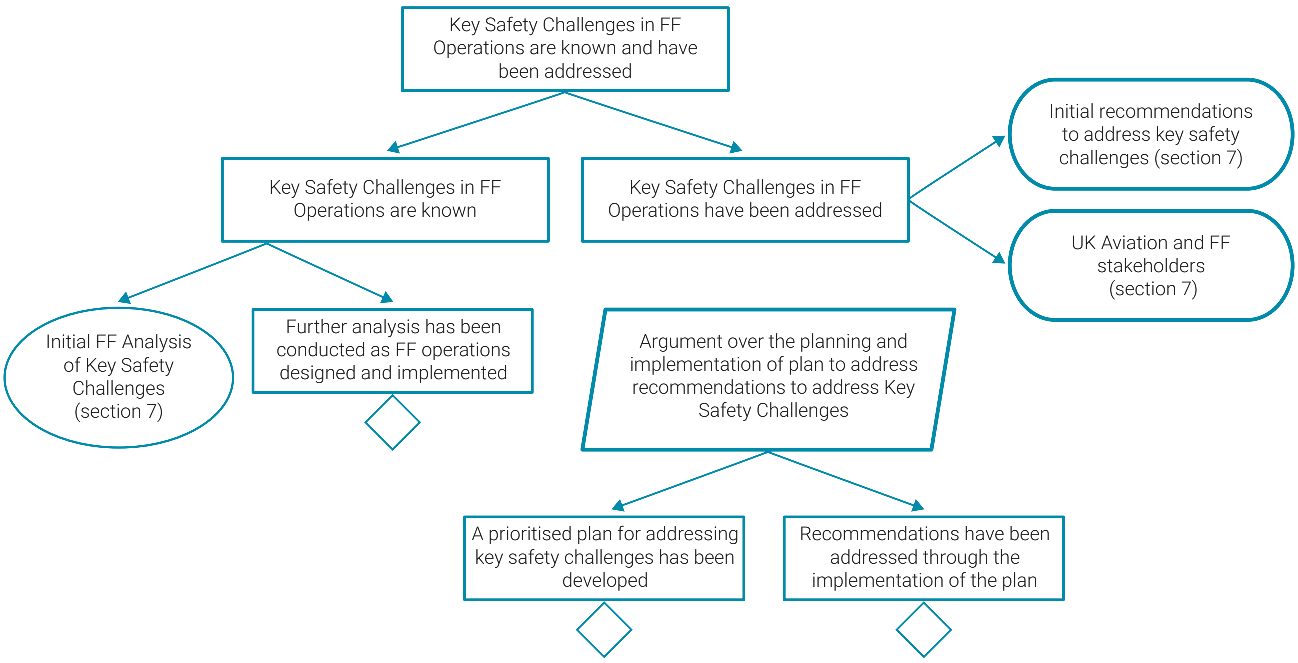
It is not expected that all safety issues can be identified through traditional risk analysis. To provide increased assurance it is beneficial to use a range of methodologies to identify and mitigate safety impacts. In addition to the bowtie risk analysis discussed above, the second pillar of the safety argument within this framework is based upon the identification and management of key safety challenges. At a whole-of-aviation-system level this approach allows for the most significant issues to be identified quickly and approaches for their management determined and implemented in a planned, expeditious manner.

Understanding the key safety challenges in FF and assuring that they have been addressed is key to ensuring acceptably safe outcomes with respect to FF integration with other UK aviation operations. The argument overleaf presents an initial argument structure to achieve this goal.

This project has conducted an initial analysis of the safety challenges associated with the implementation and growth of FF operations. The analysis will require further development as knowledge increases when FF operations are designed and implemented. This may include more detailed analysis of the transversal themes described in this project and the identification and analysis of additional challenges.

The safety challenges identified in this project for the integration of FF operations into the UK aviation system over the long-term are significant. The level of effort and co-ordination required to address certain recommendations in this document must be considered and consulted with key stakeholders to ensure effective resolution. To achieve this, it is recommended to develop a prioritised plan for addressing the recommendations and ensure the participation of appropriate stakeholders and to establish a forum for continual interaction with key stakeholders.

Progress on the safety challenges identified in this project will be best achieved through wide engagement and consultation across FF and UK aviation stakeholders. Ensuring diversity in the stakeholders involved in developing solutions and transparency in decisions to resolve these challenges will be important for the industry, given the complexity of the future aviation landscape and the number of participants. Many of the recommendations to address the safety challenges are focussed on industry-wide strategy and planning with explicit decision making (e.g. publication of concepts of operation). It will be important to consider this across the governance, management and task/technical layers of the UK aviation system (as discussed in the complex systems analysis).



Conclusions

UK aviation will change dramatically in the long-term, in large part driven by innovations in FF. In this report an initial framework has been articulated to support the future safety assurance of FF operations, and hence the ongoing safety of UK aviation. This framework is made up of four key parts:

- The identification of new FF use cases and scenarios, and an understanding of how the integration of the aviation system evolves over time in the context of these use cases;
- An analysis of the impact of new use cases on the hazards, threats and controls of the overarching aviation system;
- An analysis of key safety challenges which will have a significant impact on aviation safety into the future; and
- An initial safety framework that describes the role each component of the framework plays towards providing future assurance regarding the safety of FF operations and the aviation system.

Use cases and aviation system stakeholers

This framework has considered the use cases for FF over the short-, medium- and long-term as a basis to determine the potential changes in these three time frames. These use cases do not necessarily reflect all future changes to UK aviation, but are focussed on the evolutionary parts of the industry that are relevant to the FF challenge. In the framework a description of how the roles of key actors will evolve over the short-, medium- and long-term has been presented. With the increasing number and changing nature of stakeholders in the aviation system, it will be important to maintain this viewpoint to ensure a common understanding of the aviation system into the future.

Risk impact

The impacts of FF use cases have been considered from a risk perspective using the bowtie methodology. An analysis of both current UK safety risks and the future risk profile of operations involving drones, UAM and RAM has been undertaken to understand key considerations which will be important to the safety of future operations. This has led to a set of high-level requirements relating to necessary functions and capabilities of key system elements such as flight control and traffic management to support risk mitigation in the long-term.

Key safety challenges

Key areas of safety focus across the short-, medium- and long-term operation of FF use cases have been identified as transversal themes. Critical themes for future safety have been identified as:

- Complex Systems (and their impact on safety)
- Integrated Safety and Risk Management
- The role of human and autonomy
- Supporting Infrastructure

The significance of these themes is related to both their impact on the safety of the aviation system and the length of time and level of coordinated effort required to address them.

Recommendations

This project has identified many recommendations which will contribute to assuring the acceptably safe integration of FF operations into the future aviation system. They relate to all aspects of the system and the stakeholders within it and act as a starting point for further development.

The highest priority recommendations are listed below, and the final recommendation provides the means to address the many detailed recommendations in this report.

Recommendation 9.1 - Development of a concept of operations for the future aviation system which includes transitional states.

Recommendation 9.2 - Establishment of Target Levels of Safety for aircraft operations, including specific FF use cases.

Recommendation 9.3 - Establishment of an aviation system risk baseline made up of both the current risk profile and the future expected risk profile, based upon future concepts of operations.

Recommendation 9.4 - Prioritisation of the issues and recommendations in the report and the establishment of a safety work program in support of the FF challenge. This should include, amongst other things, a plan for managing the impacts of complex systems at the Governance, Management and Task/Technical layers. This should also include consideration of the many more detailed recommendations in this report.

Consideration should be given to placing the responsibility for developing and delivering this plan on a pan-industry body or, establishing one specifically for this purpose.

To ensure effective development of the work within this report, it will be important to undertake wide engagement and consultation across the aviation industry.

Evolution of the safety framework

It should be noted that this is an initial framework, and the evolution of FF is expected to occur over a significant period of time. Thus, the range of issues identified in this report is large and work to address them will occur over a long period of time. At this early stage of FF, it is not possible to be complete in the identification of issues and it is expected that this work will require continual enhancement as knowledge grows about the implications of FF. However, the framework approach used in this report will remain valid and can be expanded as a way of identifying and prioritising areas of focus for safety work.

To progress this work, the following recommendations are made:

Recommendation 9.5 – Presentation of the analysis and recommendations to FF participants and the wider UK aviation community to:

- Seek feedback on the completeness of the analysis and prioritisation of issues; and
- Inform planning of future work across all aviation stakeholders.

Recommendation 9.6 – Expansion of the concepts to the full UK aviation system (including other new aviation concepts such as HAPS and autonomous CAT).

Recommendation 9.7 – Identification of other additional key safety challenges that can have a critical impact on the success of future UK aviation, both within the scope of FF and other aviation innovation activities.

Recommendation 9.8 – Establishment of an international engagement strategy and plan to ensure that the UK remains central to developing and influencing globally harmonised approaches and standards.

The recommendations and actions provided above and in the main report are now the subject of ongoing discussions between industry and the regulator to determine the most effective way forward. These discussions are taking place in parallel with the necessary engagement activities with industry, academia and relevant government agencies.

However, we would value feedback on the study outputs and conclusions to inform the discussions and decision-making on the most effective way forward.

Please send any feedback to:

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