Drone Information Services

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IMPETUS

INFORMATION MANAGEMENT PORTAL TO ENABLE THE INTEGRATION OF UNMANNED SYSTEMS

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Abstract

IMPETUS D2.2 focuses on the elucidation of the information services that will be needed to realize U-Space. The document yields a coherent framework identifying key information needs that U-Space services – as of U1, U2, U3 and, to some extent, U4, will have to fulfil. Moreover, up to 35 U-Space service concepts have been elucidated and numerous of their key aspects have been thoroughly discussed.

Table of Contents

List of Tables

List of Figures

Executive Summary

IMPETUS deliverable D2.2 focuses on the elucidation of the information services that will be needed to realize U-Space.

Complementarily to the domain analysis conducted in the prior IMPETUS deliverable D2.1 [1], the methodological top-down approach adopted here was aimed at organizing all the information previously compiled into a coherent operating picture that reveals i) *how drones are envisioned to be operated in U-Space*, ii) *what information is needed to support drone operations (and why)*, and iii) *how such information might be produced*.

The work conducted is driven by a number of premises, considerations and assumptions commonly accepted by drone stakeholders, although the technical discussion developed goes into further reasoning –sometimes in the speculative realm, which is needed to find out enough level of detail to accomplish the objectives mentioned. In that process, we have resorted to additional knowledge and expert judgement as well as to profuse comparisons and analogies between legacy and envisioned concepts and solutions across manned and unmanned aviation domains in an attempt to find out key commonalities and differences, possible solutions and key challenges that require further research. In line with the objective of IMPETUS to contribute a long-term perspective to U-Space, we have focused on U3 and, to some extent, U4 services –i.e. UAS of any type operating in a ‘business as usual’ mode, including air taxi in city environments and large UAS (e.g. autonomous air cargo) having to operate in manned airspaces.

The result is a thorough rationale that provides –to the best of our knowledge, reasonable answers to the questions above to a considerable extent of detail and completeness. A different question is whether or not the manned and unmanned aviation communities agree with these answers. A preliminary cross comparison between IMPETUS D2.2 vs. the ‘Concept of Operations for U-space’ [2] just recently delivered by the sibling U-Space project CORUS [3] indicates a great deal of alignment, though also some discrepancies that will have to be further discussed. Anyhow, the IMPETUS consortium considers this document a first crafting subject to review and, we hope, much discussion to come.

1 Introduction

1.1 Scope of the document

IMPETUS' prior deliverable D2.1 (*Drone Information User's Requirements*) [1] compiled a significant amount of information about drone operations coming from a number of sources, including, pioneer drone operators and UTM service providers, ATM experts, IT experts and other UAS/ATM stakeholders from both within and outside the IMPETUS consortium.

Complementarily to the bottom-up domain analysis conducted in D2.1, the methodological top-down approach adopted here is aimed at organizing all the information previously compiled into a coherent operating picture that reveals i) *how drones are envisioned to be operated in U-Space*, ii) *what information is needed to support drone operations (and why)*, and iii) *how such information might be produced*.

To achieve these objectives, the present document addresses two further steps, namely:

1) The abstraction from the information collected in D2.1 of a *generic drone operation lifecycle* (§2.2) that aims at facilitating the harmonization of concepts and terminology, as well as the identification of the main actors, systems and functions playing a role in drone operations and, ultimately, of the elements of *information almost invariably needed*/involved (§3) in drone operations
2) The elucidation of conceptual *drone information services* (§4) that could potentially become part of U-Space to satisfy the information needs identified.

The first commonality that can be identified between U-Space and ATM is that both domains are inherently multidisciplinary and much more complex than it might seem at a first glance. Consequently this document touches many diverse disciplines in more or less depth, implicitly showing how operational concepts are tightly coupled with the capabilities and limitations of the technologies that they rely upon, as well as with many other aspects such as legal, regulatory, economic, etc. This gives rise to a great deal of complexity. Additionally, decomposing operations is usually a bit more complex than breaking down structure.

Thus, to facilitate reading and understanding this document, the discussion is structured in an incremental level of detail. Firstly, §2 introduces the methodological approach adopted and subsequently uses it to propose a high level answer to objective i) above. Then §3 goes into further detail in order to find answers to question ii). Finally, §4 devises solutions to the previously identified issues as well as defining new ones.

When developing the technical discussion a number of premises and considerations have been taken into account:

- Focus on safety issues first –security and privacy are addressed to some extent, though not as thoroughly
- Focus on operational aspects – operations-centric approach. The aerial platforms are assumed to be airworthy –i.e. they implement reasonable redundancies for the safety-critical systems
- Borrow as many concepts and terminologies from the ATM realm as applicable to facilitate understanding and buy-in by traditional aviation actors (users, regulators, etc.)

- Frame issues and solutions within the corresponding state-of-the-art in ATM and UAS
- Maintain a long term perspective to avoid U-Space diverging from ATM (focus on U3 as well as on U4 to some extent) –we believe that drone insertion in the airspace is both coupled and synergistic with the modernization of the ATM system
- Anticipate reasonable solutions to the issues identified, no matter if they are speculative –the need is about drafting a reasonable picture that both the unmanned and manned aviation communities can be confronted with as soon as possible so we can move forward from there
- When proposing solutions, define how they could be enabled through a step-wise approach – evolutionary, rather than revolutionary, in line with the envisaged U-Space evolution (U1, U2, U3 and U4)
- Maintain an implementation-agnostic approach to the largest extent possible
- Consider/anticipate feasibility and affordability implications to the best of our knowledge
- Consider how the proposed solutions might challenge manned aviation status quo
- Other considerations are legal, liabilities, economics, etc.

Regarding the scope of the discussion, most of it refers to either *operations planning* aspects (the so-called *strategic* and *pre-tactical phases* in manned aviation) or *operations execution* (*tactical phase*) while the aerial vehicle is airborne. The specific problems related with ground operations as well as with the transition between ground and air and vice versa are left out of the scope. Likewise, most mission-specific aspects except those considered relevant to U-Space are also left out of scope.

1.2 Intended readership

This document is intended to be used by IMPETUS members, the SJU (included the Commission Services) and the community of drone stakeholders in general.

The document will be exchanged with those exploratory research projects with high dependencies with IMPETUS such as the project in charge of the definition of the U-Space concept of operations, CORUS, and the other project in same research topic, DREAMS.

1.3 List of Abbreviations

UTM acronym is used in this document for the general notion of a drone traffic management system and not for the specific system which will be designed in the USA.

Abbreviation	Description
2D	Two-Dimensional
3D	Three-Dimensional
3G/4G/5G	3rd/4th/5th Generation
3GPP	3rd Generation Partnership Project
4D	Four-Dimensional
4DTRAD	4D Trajectory Datalink

Abbreviation	Description
A/A	Air/Air
A/G	Air/Ground
ABL	Atmospheric Boundary Layer
ACARS	Aircraft Communications, Addressing and Reporting System
ACAS-X	Aircraft Collision Avoidance X
ADS-B	Automatic Dependent Surveillance - Broadcast
ADS-C	Automatic Dependent Surveillance - Contract
AGL	Above Ground Level
AIM	Aeronautical Information Model
AIS	Aeronautical Information Service
AIXM	Aeronautical Information Exchange Model
ANSP	Air Navigation Service Provider
AOA	Angle of Attack / Angle of Arrival
AOC	Airline Operations Center / Air Operation Certificate
AOS	Angle of Sideslip
APM	Aircraft Performance Model
ARF	Advanced Research Forecast
ASAS	Airborne Separation Assurance System
ASL	Above Sea Level
ATC	Air Traffic Control
ATCO	Air Traffic Control Officer
ATFM	Air Traffic Flow Management
ATM	Air Traffic Management
ATS	Air Traffic Services
ATZ	Airfield Traffic Zone
AV	Aerial Vehicle
BRLOS	Beyond Radio Line of Sight
BVLOS	Beyond Visual Line of Sight
C2	Command & Control
CA	Collison Avoidance
CAA	Civil Aviation Authority
CFD	Computational Fluid Dynamics

Abbreviation	Description
CFIT	Controlled Flight Into Terrain
CNPLC	Control and Non Payload Communications
CNS	Communications, Navigation & Surveillance
CNS+I	CNS plus Information management
COA	Certificate of Authorization
COM	Communications
ConOps	Concept of Operations
COTS	Commercial-Of-The-Shell
CPDLC	Controller-Pilot Data Link Communications
CTOL	Conventional TakeOff and Landing
DAA	Detect and Avoid
D-ATIS	Digital Automatic Terminal Information Service
DEM	Digital Elevation Model
DGIS	Digital Geographical Information Service
DLT	Distributed Ledger Technologies
DME	Distance Meassurement Equipment
DSM	Digital Surface Model
DTM	Digital Terrain Model / Drone Traffic Management
DTT	Digital Terrestrial Television
D-VOLMET	Digital meteorological information for aircraft in flight
EAS	Equivalent AirSpeed
EASA	European Aviation Safety Agency
ECMWF	European Center for Medium-Range Weather Forecasts
EFT	Emergency Flight Termination
EGPWS	Enhanced GPWS
EKF	Extended Kalman Filter
ELT	Emergency Location Transmitter
EO	Electro-Optical
FDOA	Frequency Difference of Arrival
FIS-B	Flight Information Service - Broadcast
FLARM	Flight Alarm
FOV	Field of View

Abbreviation	Description
FP	Flight Planning
G/G	Ground/Ground
GCS	Ground Control Station
GDOP	Geometric Dilution of Position
GIS	Geographical Information System
GNC	Guidance, Navigation & Control
GNSS	Global Navigation Satellite System
GPRS	General Packet Radio Service
GPS	Global Positioning System
GPWS	Ground Proximity Warning System
GS	Glide Slope
GSM	Global System for Mobile (communications)
HMI	Human-Machine Interface
HW	Hardware
IAS	Indicated AirSpeed
ICAO	International Civil Aviation Organization
ID	Identity / Identifier
IFC	Instrument Flight Conditions
IFR	Instrumental Flight Rules
ILS	Instrument Landing System
IMU	Inertial Measurement System
INS	Inertial Navigation System
IoO	Illuminator of Opportunity
IR	Infra-Red
JARUS	Joint Authorities for Rulemaking on Unmanned Systems
LES	Large-Eddy Simulation
LiDAR	Laser Imaging Detection and Ranging
LoA	Loss-of-Authority
LOC	Localizer
LoC	Loss-of-Control
LoE	Loss-of-Engine/Energy
LoG	Loss-of-GPS / Loss-of-GNSS

Abbreviation	Description
LoL	Loss-of-Link
LoS	Loss-of-Separation
LTE	Long-Term Evolution
MAC	Mid-Air Collision
MACH	Mach number
MEL	Minimum Equipment List
MEMS	Micro Electro-Mechanical System
METAR	Aerodrome Routine Meteorological Report
MOPS	Minimum Operational Performance Standard
MTOM	Maximum TakeOff Mass
MW	Middleware
NAA	National Aviation Authority
NAV	Navigation
NextGen	Next Generation Air Transportation System
NFZ	No-Fly Zone
NOAA	National Oceanic and Atmospheric Administration
NOTAM	Notice to Airmen
NOTDO	Notice to Drone Operators
OA	Operational Authorization
OAT	Outside Air Temperature
OGC	Open Geospatial Consortium
PBCS	Performance-Based Communications & Surveillance
PBN	Performance-Based Navigation
PIC	Pilot In Command
PL	Payload
PRNAV	Precision Area Navigation
PSR	Primary Surveillance Radar
PVT	Position, Velocity & Time
PWS	Predictive Wind Shear
QAM	Quadrature Amplitude Modulation
QFE	Atmospheric pressure at Field Elevation
QNH	Atmospheric pressure at sea level (Nil Height)

Abbreviation	Description
QoS	Quality of Service
R&D	Research & Development
RA	Resolution Advisory
RAIM	Receiver Autonomous Integrity Monitoring
RF	Radio Frequency
RLOS	Radio Line of Sight
RLP	Required Link Performance
RNP	Required Navigation Performance
RPA	Remotely Piloted Aircraft
RPS	Remote Pilot Station
RSSI	Received Signal Strength Indication
RTCA	Radio Technical Commission for Aeronautics
RWC	Remain Well Clear
Rx	Receiver
SARPS	Standard and Recommended Practices
SATCOM	Satellite Communications
SESAR	Single European Sky ATM Research
SIGMET	Significant Meteorological information
SOO	Signal-of-Opportunity
SORA	Specific Operational Risk Assessment
SP	Service Provider
STOL	Short TakeOff and Landing
SUR	Surveillance
SVO	Semi-direct Visual Odometry
SW	Software
SWAP	Size, Weight and Power
SWIM	System-Wide Information Management
TAF	Terminal Aerodrome Forecast
TAS	True AirSpeed
TAWS	Terrain Awareness Warning System
TCAS	Traffic Collision Avoidance System
TDOA	Time Difference of Arrival

Abbreviation	Description
TIS-B	Traffic Information Service - Broadcast
TLS	Target Level of Safety
TMA	Terminal Manoeuvring Area
TOA	Time of Arrival
TP	Trajectory Prediction
TV	Television
Tx	Transmitter
UAS	Uninhabited/Unmanned Aerial System
UAT	Universal Access Transceiver
UAV	Unmanned Aerial Vehicle
UHF	Ultra High Frequency
UML	Unified Modelling Language
UOC	User Operation Center
UTC	UAS Traffic Control
UTM	UAS Traffic Management
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
VDL	VHF Data Link
VFC	Visual Flight Conditions
VFR	Visual Flight Rules
VHF	Very High Frequency
VLOS	Visual Line of Sight
VOR	VHF Omni Range
VPN	Virtual Private Network
VTOL	Vertical TakeOff and Landing
WP	Waypoint
WRS	Weather Radar System
WXXM	Weather Information Exchange Model

2 Approach to the identification of drone services

2.1 Methodology

Drones represent a great deal of novelty in aviation. Not only the variety of UAS types, components, technologies, performances, capabilities, limitations, applications and *modus operandi* is huge, but it keeps increasing at a very fast pace. This large heterogeneity and dynamism creates complexity and confusion, which makes it difficult harmonizing concepts and terminology, as well as technology solutions, standards and regulations.

Thus, one major challenge confronted by U-Space is the need to create a *common operating picture* that holds reasonably stable in such a rapidly evolving environment. At the same time, this picture needs to be conceptualized for future circumstances that are not yet validated. Another challenge is to make that operating picture understandable by traditional aviation actors, so similarities and differences between manned and unmanned operations can respectively be taken advantage of and addressed as appropriate.

We propose to formulate this common operating picture in terms of a *generic drone operation lifecycle* model (§2.2) that may represent any possible drone operation based on, essentially, the same generic actors, systems and functions, the interactions among them and the elements of information involved in these interactions.

The proposed modelling methodology to reach such a generic drone operation lifecycle model is based on the concept of *domain invariants*. The analysis of numerous UAS and drone operations use cases reveals that, although much dissimilarity exists among them, numerous commonalities can also be identified. Such commonalities may be found in both the structural and behavioural aspects of the UAS and their operations. The common elements and functions that may conceptually be present across all UAS and their operations are referred to as *invariants* of the U-Space domain. The domain invariants are not independent from each other; instead, they are connected by structural and behavioural relationships (e.g. interactions) that may be themselves invariant as well, leading to what is called a *metamodel*. A domain metamodel can be characterized as an abstract generic model built in terms of domain invariants. Thus, what we are looking for is a metamodel of drone operations, i.e. a sort of template that any particular drone operation model can be considered an instance of.

Metamodeling is a powerful modeling approach whose benefits are manifold:

- Allows coherent classification and integration of existing specific/particular models
- Improves consistency, completeness and correctness, leading to better model specifications so far it easies the identification of a reduced number of more orthogonal modelling primitives
- Saves effort and improves quality, as long as the key features that can be addressed at the metamodel level remain valid for the specific/particular models

- Resists changes, diversity and uncertainty[1] of different nature, including significant domain transformations, as it is founded on invariants

The description of the particular/specific UAS and UAS operation models in terms of the abstract elements[2] and ontology introduced by the metamodel constitutes in fact a *'common language'* to talk about the different aspects of the domain. This – we hope, will contribute to clarify and exchange ideas and, consequently, improve domain knowledge and understanding and harmonize concepts and terminology.

Figure 1 follows the OMG [4] lingo to illustrate how metamodeling can be applied to the drone operations domain.

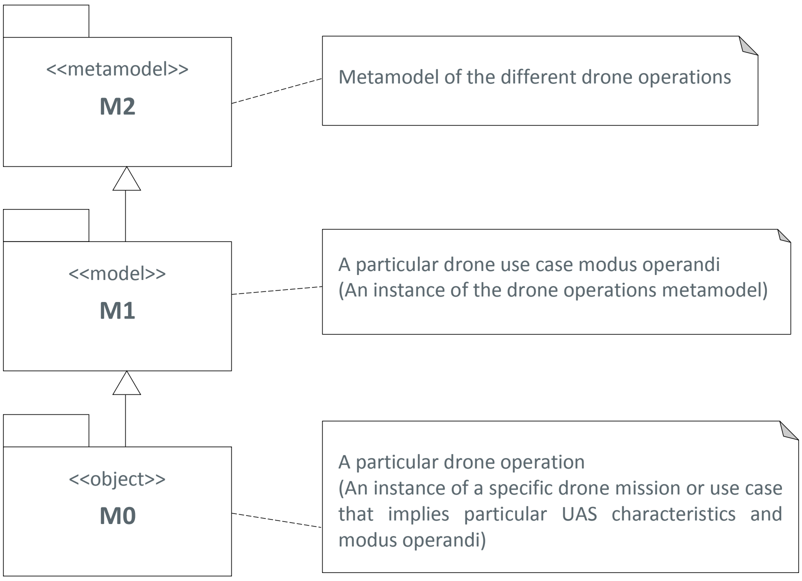

Figure 1: 3-level abstraction hierarchy of drone operation models

In Figure 1, the representative use cases of drone operations included in D2.1 would fit within the UML (Unified Modeling Language) package stereotyped as <<model>> and labelled **M1** (level-1 model). Examples of level-1 models could be any particular drone use case or mission that implies a specific modus operandi.

Level-1 models are not yet specific drone operations. To become specific, level-1 models have to be specialized[3] to a particular drone performing a specific drone operation instance – including planning and executing a particular trajectory in concrete space and time. The corresponding Level-0 model is depicted in Figure 1 as a UML package stereotyped as <<object>> and labelled **M0**.

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[1] The uncertainty about the U-Space operational concept to be proposed by the sibling project CORUS [3] is of particular importance, since such a concept and the services that shall realize it are deeply interrelated

[2] E.g. in our metamodel we adopted the term *'traffic planning'* to denote the abstraction of any traffic-related planning service such as the ones that could mimic within the U-Space domain ATM concepts such as *Air Traffic Flow Management* (ATFM), also referred to as *capacity and demand balance* or *network management*.

[3] Generalization-specialization relationship is represented in UML as a line with a triangular arrowhead pointing to the more general element.

The highest level of abstraction corresponds to the advocated metamodel, represented in Figure 1 as the UML package stereotyped as <<metamodel>> and labelled **M2** (level-2 model). As depicted in the figure, the metamodel is a generalization of all level-1 models or, in other words, any level-1 model is a specialization of the metamodel.

The basis for the identification of domain invariants, upon which the drone operations metamodel builds, is the *domain analysis* conducted in D2.1, which compiled a significant amount of information about diverse drone operations coming from a variety of sources, including, pioneer drone operators and UTM service providers, ATM experts, IT experts and other UAS/ATM stakeholders from both within and outside the IMPETUS consortium. D2.1 provided numerous examples (instances) of M1-level, i.e. drone operation models, as well as many referents belonging to the manned aviation domain.

From there, section §2.2 aims at reaching M2-level, i.e. abstracting out a metamodel of drone operations consistent with all the M1-level models surveyed, as well as, to the extent possible, analogous to the manned aviation domain (ATM).

The metamodel described in §2.2 reveals, in particular, the main steps typically found in a generic drone operation lifecycle along with the principal actors and functions involved in each step. This helps further distilling the elements of information almost invariably needed, in general, to support drone operations, which is done in section §3 (Invariant information needs).

Finally, in view of the information needs found and based upon the knowledge, experience and expert judgement available to the IMPETUS consortium, we propose in section §4 the list of candidate U-Space services that might in general fulfil such information needs regardless the specific U-Space operational concept ultimately adopted[4].

2.2 Generic drone operation lifecycle

We start the process of finding out a generic *drone operation lifecycle* in the context of a *UAS operations management system* such as U-Space by abstracting how the *value chain of UAS services* looks like in general. This is reflected in Figure 2, which represents the 13 main elements almost invariably found (at least notionally) in any of the UAS business and use cases compiled in D2.1 [1] .

Essentially, the great majority of UAS business cases thinkable[5] pursue delivering a *UAS service* (13) to certain *customer* sitting at the end of the value chain. The UAS service may consist on the collection and delivery of goods (e.g. packages, liquids, parts, etc.) or people (e.g. passengers) to a destination location, or on the delivery of information derived from the one collected by sensors aboard the UAV. This requires that (1) the *payloads* (e.g. packages, items, sensors or passengers) and (2) the *UAV platforms* are fitted together and that a *UAS operation* is conducted (3-11), possibly with the assistance of (12) certain *exploitation services* (e.g. mission data processing or any other assistance to the mission not directly implied in its planning or execution).

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[4] The expectation is that the U-Space operational concept delivered by CORUS [2] should map somehow to the drone operations metamodel developed here (in notional terms, possibly with different terminology), otherwise the metamodel should have to be further generalized.

[5] A possible exception being drones operated just for fun, like in the case of leisure or entertainment operations and shows or demonstrations of multiple drones operating in coordinated choreography

The accomplishment of the UAS operation involves that it has to be launched from and recovered at certain *UAS launching and recovering facilities* (3), which may be of exclusive use or shared with other airspace users. The operation has to be planned and subsequently executed, although re-planning may still be needed at any time during the execution process. UAS *operations planning* (6-8) and *execution* (9-11) processes (including UAV launch and recovery and surface movement, in its case) must be supported by (4) *CNS+I infrastructures* (Communications, Navigation, Surveillance and Information management), as well as by (5) a number of *common services* providing relevant operational information (e.g. registry, identification, geospatial, aeronautical, weather, etc.).

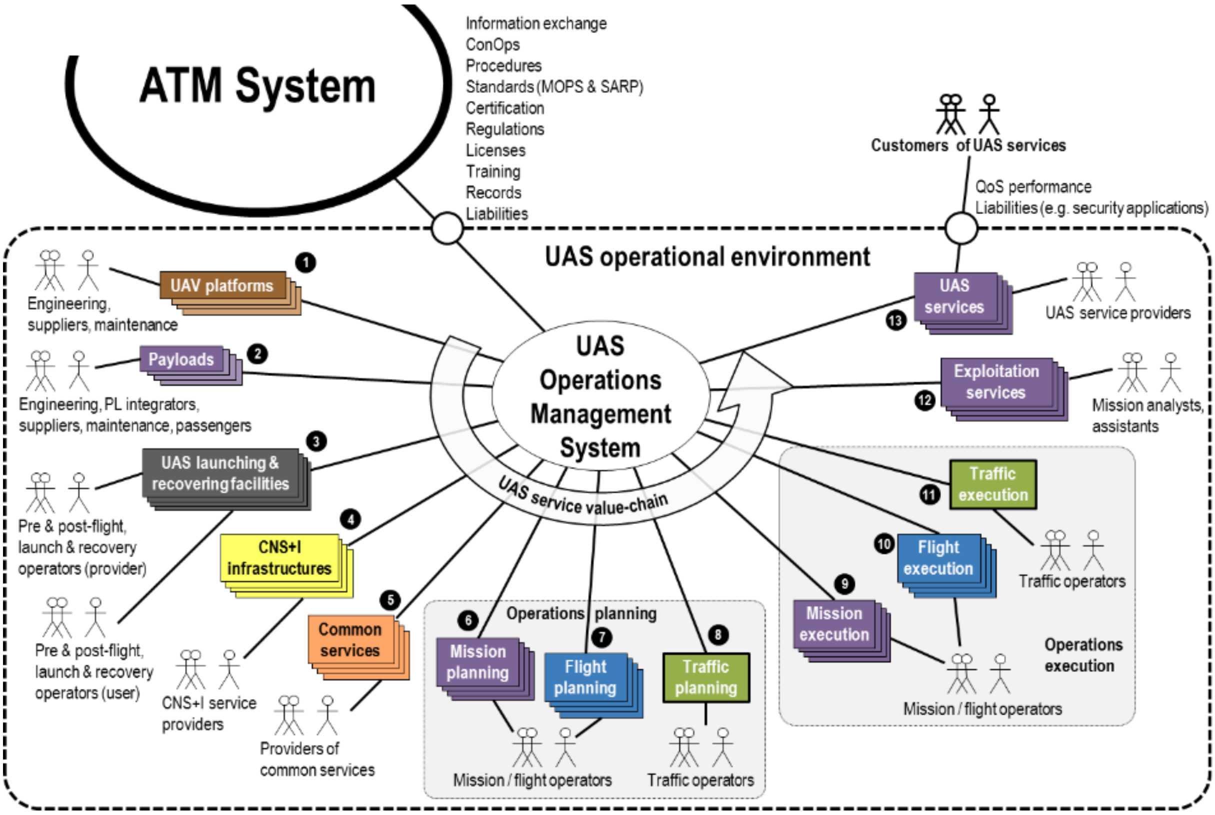

Figure 2: The value chain of UAS services

In general, the drone operation considered may not be performed unrestrictedly and in isolation, but in a traffic context subject to numerous constraints, where other airspace users (whether manned or unmanned) may interfere (e.g. causing *losses of separation* - LoS) or even compete for scarce resources (frequencies, airspace, time slots, use of shared launching/recovering facilities, etc.). Thus, the UAV trajectory must not only fulfil the requirements of the *mission* (6 & 9), but also be doable and acceptable according to, respectively, vehicle capabilities (e.g. performance, equipment capabilities and limitations) and operational context restrictions (e.g. no-fly zones) from an isolated *flight* perspective (7 & 10). This leads to the notion of *user-preferred trajectory* (UPT), which is the trajectory that an airspace user would prefer for the sake of mission merit, considering the general restrictions applicable in the given operational context. Assuming that concurrent demand of multiple (potentially many) UAS operations in the same airspace will likely entail airspace capacity issues and/or separation issues, all UPTs that are not acceptably separated in space or time may not be allowed to be performed as planned, and thus particular amendments may result necessary. Here is where the *traffic* management services (8 & 11) come into play with a critical role, possibly at both planning and execution timeframes.

Finally, the UAS service contract between the *UAS service provider* and the customer may require that certain *quality of service (QoS) performance* is met, as well as, in certain cases, be subject to liabilities (e.g. when security-critical aspects are involved in the UAS use case). On the other hand, the interface between the UAS service management system and the *ATM system* is concerned with a number of aspects such as ConOps, information exchange, procedures, standards (MOPS & SARPS), certification, regulations, licenses, training, records, liabilities, etc., to a large extent undetermined as of today.

In view of the above, a generic drone operation lifecycle could be *notionally*[6] described as follows:

At planning level, the lifecycle starts with *mission planning* (6), which translates mission requirements set up by a *mission operator* or *system* into specific actionable tasks for all the functional elements involved in the performance of the mission.

In particular, the mission planning process needs to interact (typically in an iterative way) with a *flight planning* (7) process to design the trajectory to be flown by each UAV taking part in the mission (the mission may involve a fleet of UAVs). The mission planning does so in terms of a sort of trajectory recipe or *flight plan* by means of the trajectory building primitives provided by the flight planning capability (waypoints in typical UAS legacy systems). To guarantee safety, the flight planning process must first make sure that the trajectory being designed is feasible for the specific UAV that shall perform it; second, that such trajectory fulfils all the constrains applicable in the operational context within which the trajectory shall take place and; third, that when considered along with all the other trajectories planned by other airspace users within such spatial and temporal context, no major traffic congestion problems will arise, which might saturate the capacity of the *traffic management services* to ensure appropriate separation among all the aerial vehicles at execution time.

A rigorous flight planning process should perform the first two steps based on what-if using a sort of prediction of the trajectory that would result when the given UAV executes the flight plan under consideration in a predicted atmospheric scenario. All this processing requires the support of a sort of *"trajectory prediction"* function, a predictive atmospheric model providing the *atmospheric conditions* relevant to the flight (essentially wind, pressure and temperature), a model providing the *aircraft-specific performance characteristics*, and *geographical as well as aeronautical information* relevant to the safety of the operation, which allows checking for terrain and obstacle clearance and other operational context constrains such as airspace boundaries and no-fly zones (NFZs). All these services, along with others such as drone *registry* and drone *identification* are collectively referred to in Figure 2 as *common services* (5).

Nevertheless, the design of a safe trajectory within a traffic environment (where multiple UAS operate concurrently, and so their trajectories may potentially interact) requires the third step, i.e. the flight planning process to interact with a *traffic planning* (8) process (somehow analogous to the so-called *traffic flow management* in the ATM domain), which cares about traffic issues that might

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[6] Meaning that, perhaps in some cases, some of the elements and processes explained may not even have a more or less sophisticated physical referent because they only exist within the operators' minds, or because they are trivial. One example is mission-driven trajectories, where flight planning and execution occur simultaneously rather than sequentially

arise if the demand of UAS operations (flight plans) is unbalanced with respect to the UAS operations management system *capacity*. Once the cycle *mission-flight-traffic planning* is successful, the requested UAV trajectory is allocated and scheduled for execution; otherwise a feedback chain from the bottom-up informs the mission planning process that changes need to be made to the *mission trajectory* in order to make it acceptable. When the process is completed for each UAV trajectory encompassed by the mission, the whole mission is allocated, i.e. scheduled in space/time and approved for execution.

Since a considerable amount of uncertainties are present at planning level (atmospheric conditions, trajectory execution fidelity vs. the flight plan, flight contingencies and mission issues that may require dynamic mission re-planning), missions are frequently not performed exactly as planned. To ensure the safe accomplishment of the planned UAS operations (i.e. to cope with the effects of the uncertainties at operation-time) three new processes come into scene at execution level to respectively support the *mission*, *flight* and *traffic* lanes of the drone operation lifecycle.

At execution level, then, the lifecycle proceeds with *mission execution* (9) triggering the execution of the mission plan of each UAV participating in the mission, which, down the stream, causes *flight execution* (10) to trigger the execution of the corresponding flight trajectory and *traffic execution* (11) to start managing the separation of such flight along with the rest of the traffic system. Mission execution and flight execution functions are typically partially allocated to the ground segment, -specifically to the ground control station (GCS) or, more generically, the *user operations center* (UOC), respectively supervised by *mission operators* and remote *pilots-in-command* (PICs), in charge of remotely monitoring and managing the *mission and flight performance to plan* for all the participant UAVs. The other part of the job, which requires shorter control-horizons, e.g. *payload control* and *flight control* and/or short-term autonomous responses, e.g. *payload or mission management,* or *flight management* actions in response to *in-flight contingencies*, may need to be performed aboard each single UAV – to some extent autonomously, by means of the respective airborne mission and flight execution counterparts.

The execution process concerning *flight* (10) and *traffic* (11) requires critical support from three key infrastructures, namely *communications* (including *command and non-payload communications*, CNPLC), *navigation* and (traffic) *surveillance*, classically known as *CNS infrastructures* (4) in the manned aviation domain, plus an equivalent within the U-Space context to SWIM (*System-Wide Information Management*) [5], which would enable the appropriate networking environment for all the distributed heterogeneous functions/subsystems to interact among them and share data through diverse data exchange paradigms – CNS+I (4). CNS infrastructures will have in general both ground and airborne components. At execution time the CNS infrastructures must not only provide the communications (including C2), navigation and (traffic) surveillance capabilities as required but, also, *monitor* that the respective *QoS performances* remain within acceptable limits or, otherwise, trigger the appropriate *alerts*. At planning level, the CNS infrastructures must also support safety through providing *predictive* capabilities of their respective *QoS performance*.

As a result of cumulative uncertainties that lead to larger than acceptable deviations with respect to plan, or because sudden unexpected events such as traffic, flight or mission contingencies, or just due to the highly dynamic nature of a mission even in nominal circumstances, any of the three functions involved in the *mission-flight-traffic execution* loop might raise the need for dynamic changes that end up requiring one or several UAVs to dynamically modify trajectories. This would require that mission, flight and traffic planning functions carry out a re-planning cycle while-on-the-fly, in coordination with the corresponding execution functions.

In addition to supporting safe execution of UAS operations (which concerns the *flight* and *traffic* processes), the UAS operations management system must ensure their effectiveness and cost-efficiency, which involves additional mission-critical elements, namely, *mission communication infrastructures* that enable exchange of mission data between air and ground segments (A/G), ground/ground (G/G) and, for some missions, air/air (A/A), as well as, automated *mission data processing and exploitation capabilities/services* (12) that may be required to be partially allocated on board or to the ground segment and work either in operation-time or in post-operation to minimize mission operators and analysts workload to the extent possible. This completes the UAS service lifecycle.

Finally, a set of distributed *data recording functions* must be present on board, as well as on the ground to ensure that mission-critical and flight-critical data are collected and recorded all over the system throughout the drone operation lifecycle in order to enable post-operation mission/flight QoS performance assessment, troubleshooting and, ultimately, an official source of data for safety investigations – as it is mandatory in the manned aviation domain, as well as *security*, *privacy* or other *law enforcement* evidences.

Whereas knowledge and solutions related to the initial[7] and final[8] elements of the UAS services value chain represented in Figure 2 are commonplace across the UAS community, much lower awareness exists about the elements in the middle (4 to 11) in communities others than those related to manned aviation (where safety is the number one priority), such as CAAs, aviation safety agencies and ATM. However, such elements (4-11) are the most critical ones concerning safety and, thus, the UAS insertion regulatory process and, consequently, the most important ones to enable U-Space. The drone operation lifecycle model presented precisely aims at setting up a framework to enlighten how such elements look like.

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[7] UAV platforms (1), Payloads (2) and UAS launching & recovering facilities (3)

[8] UAS services provided to the final customer (13) and mission services such as specific mission data processing and exploitation (12)

3 Invariant information needs

Based on the generic drone operation model explained in §2.2, this section deals with distilling the list of information elements invariably needed in general to support drone operations – i.e. those that future U-Space services would be expected to provide. This does not mean that all possible drone operation instances (M0) or the drone operation models (M1) that they conform to use all the pieces of information described in their entire scope. Specific drone operations might specialize the type and amount of information required, which includes partially or totally skipping some pieces of information, should the particular operational context and circumstances make it convenient.

When identifying information needs, an effort has been made to anticipate possible solutions to the UAS insertion issues discussed in §A.1 of Appendix A, which U-Space is meant to address in the long term. This responds to a major objective of the IMPETUS initiative, which is to contribute a long-term perspective to the elucidation of the U-Space services with focus on U3 and, to some extent, U4 timeframes.

The description of the invariant information needs hereafter focuses on *what* information is thought to be needed and the justification of *why*. The discussion is organized almost following the information categories enumerated in D2.1.

3.1 Aeronautical

Future *aeronautical information* services in the context of U-Space shall have to be tailored to support the great heterogeneity of UAS operations within a given, formally defined airspace volume.

Today, manned aviation looks at distances in miles; standard horizontal separation is usually 3 or 5 miles. However, separation between drones could potential be measured in metres, therefore the information must be more precise. The level of precision now required around the safety-critical aeronautical information has not been necessary before, hence our ability to obtain the appropriate level of granularity will be a significant challenge.

Introducing *capability levels*, based upon drone equipage, UAS traffic management capabilities and the capabilities and limitations of other supporting services and infrastructures (e.g. CNS, weather, terrain and obstacle data, etc.) will improve safety, ensuring drones only operate in airspace where they have the appropriate licenses to do so; protecting the general public as well as other airspace users.

It is crucial to guarantee that UAS operations are only conducted within the assigned airspace and in full compliance of airspace structure, layout and constraints, including *geofencing*, and that aeronautical information is kept up to date. Airspace data might be ‘static’ data, update on a regular basis (daily or weekly) but as more technology is introduced, aeronautical information could be uniquely generated affecting individual flights or operations. Aeronautical information could potentially become highly dynamic, thus keeping a trusted source of such information will be paramount to ensure safety, as well as a solid scheme of responsibilities.

Another consideration which must be addressed is obstacle mapping. Safeguard zones are already published for many airports, but obstacle mapping across entire states or cities has up until now not been needed. Pre-established emergency landing sites must be identified; these could be unique to the type of airframe, i.e. VTOL or fixed wing, or the payload and equipment capabilities of the drone.

The aeronautical information needed for full drone integration is significant and ensuring data quality will pose a major challenge.

Table 1 outlines representative elements of aeronautical information relevant to drone operations.

Aeronautical information aspects	**Data representation**	**Timeframe**	**Purposes**
Aeronautical information provider ID	Unique SP identifier (alphanumeric code)	Planning, execution & post-flight	Operational, Administrative
Airspace structures Drone-only zones No-drone zones ATM-zones	Geofencing primitives, relevant attributes (e.g. type, identification, geometry description, usage, permanent/temporary flight restrictions by type of UAS, capabilities, etc.) and data quality information (accuracy, currentness, time of applicability, etc.) Flight restrictions may include separation minima, speed restrictions, MTOM restrictions, mission restrictions, etc.		
Drone navigation aids Conventional navaids Non-conventional navaids (e.g. SOO)	3D position, relevant attributes (e.g. type, identification, frequency/signal characteristics, service status, etc.) and data quality information		
Routes and procedures	(Where fixed drone procedures or routes are adopted)		
Drone ports (takeoff/launching and landing/recovering emplacements)	Location, attributes (e.g. type, identification, facilities, contact information, operational restrictions, etc.) and data quality information		
Emergency drone recovery locations	Location, attributes (e.g. geometry definition, limitations, etc.) and data quality information		
NOTAMs and Notices to Drone Operators	Notice content, attributes (addresses, issuance date & time, applicability time, validity period, etc.) and data quality restrictions		

Table 1: Summary of representative aeronautical information relevant to drone operations

3.2 Geospatial

In a wide range of drone related services and operations, the utilization and creation of georeferenced data is indispensable. This can be experienced in the need to generate accurate and collision free flight paths as well as in the creation of maps and remote sensing protocols. In consequence, the provision of geospatial data models for storage, exchange and management purposes is a core requirement to enable drone operations. These geospatial data sets represent various kinds of spatial information that is georeferenced to the coordinate system of the planet: e.g. elevation models, locations of buildings, vegetation or type of terrain. Another key attribute is that they consist of multiple different formats, types and sources. For the elaboration of a data management, a standardized structure has to be implemented. Examples for such efforts are for instance provided by the Open Geospatial Consortium (OGC), which published several specification protocols to describe harmonized data models for the representation of geographic features, interoperable locations and geospatial technologies, including the Geographical Information System (GIS). In general, geo-data can be coded by two different principles: vector and raster geodata. The first one is defining structures by geometric entities such as points, lines, knots and edges. The second one is storing data in a grid representing single pixels and cells with a certain resolution and associated attributes. Each form has its own advantages and the type of application decides which one is more suitable.

For drone operation purposes the focus shall first be set on a) relatively static information that captures the terrain in a certain area and b) rather dynamic information such as obstacles to airborne UAS. As discovered in D2.1, both types are relevant in flight planning and execution timeframes for all examined use cases. However, the strategic (planning) and post-flight phases show use case-dependent differences, which can also be linked to the depth of the research method. Data traditionally used in manned aviation describes this geospatial information in a very schematic and functional way. Since drone operations can differ strongly to those of manned aviation, the data found there often lacks the necessary level of detail and richness of information. Consequently, the access and aggregation of multiple sources is required and poses one of the great challenges in drone information management, especially with regard to the validation and verification of data.

Table 2 describes examples for types of geospatial information relevant to drone operations.

Geospatial information aspects	**Data representation**	**Timeframe**	**Purposes**
Geospatial information provider ID	Unique SP identifier (alphanumeric code)	Planning, execution & post-flight	Operational (e.g. automatic shortest path calculation, terrain and obstacle avoidance, mission-specific applications) Administrative
Terrain	2D distribution		
Imagery	2D distribution		
Obstacles	2D/3D distribution		
Vegetation	2D/3D distribution		
Population	2D distribution		
Environmental-sensitive areas Wildlife Noise	2D distribution		
Geospatial information quality	Quality information (accuracy, currentness, time of applicability, etc.)		

Table 2: Summary of representative geographical information relevant to drone operations

3.3 Weather

All drones in outdoor applications need to operate exposed to atmospheric conditions. It is well known that meteorological phenomena have a key impact on the safety of flight operations – drones not being an exception - and their prediction in the short/medium term (*forecast*), as well as its real-time estimation (*nowcast*) are essential to both when planning such operations and during their execution. Thus, information about atmospheric conditions like wind, pressure, temperature, precipitation, icing conditions, visibility, etc. is unescapably required to determine whether or not a particular drone, with particular performances, capabilities and limitations can safely operate in a certain piece of airspace during a given time interval.

Over the last two decades, aeronautical meteorology has evolved considerably from relatively simple reports such as METAR [6], TAF [7] & SIGMET [8] provided by official meteorological agencies or based on local aerodrome observations to sophisticated computer models. These models provide the spatial-temporal (4D) numerical distributions of a multitude of atmospheric variables, which are used mostly in planning but, also increasingly, during the execution of flight operations [9]. However, with regard to light UAS and/or operations at low altitude, as well as emerging concepts of on-demand urban air mobility, the proximity to the ground surface and the interaction of the wind flow with human constructions, the orography of the terrain and high vegetation represent great additional challenges. A very important one is that these vehicles, being significantly more vulnerable to adverse wind effects like turbulence, gusts and shear than traditional heavier manned aircraft, need to operate in a context where such effects are commonplace.

Traditional global or meso-scale meteorological models simply cannot achieve sufficient spatial resolution to provide a reasonably accurate forecast of meteorological effects at local geographic scales. Only recently are some models of micro-scale starting to appear [10][11][12][13][15], however whether they can satisfactorily solve the requirements necessary to support the operation of light UAS at low altitude (within the boundary layer of the terrain) and urban air mobility concepts remains an open question. One of the main causes of the possible inadequacy of existing micro-meteorology models to the aforementioned operations is that they do not capture the local wind effects such as gusts and turbulence. Another reason is that they usually follow a deterministic approach, which does not allow providing a measure of the uncertainty associated with the weather predictions.

Weather-related information may be operationally needed at different timeframes and geographical scales, for different purposes, and its accuracy may imply different levels of criticality. For instance, when planning wind-optimal trajectories, all that is needed is to know the 4D forecast of average wind field. The accuracy in this case would mainly impact efficiency and only marginally safety, should a reasonably conservative policy of fuel/energy reserve be adopted. However, when it comes to executing the planned trajectory, a great deal of operational, and in particular safety issues can appear associated to the local wind effects experienced like turbulence, gusts, thermals, shear, etc. which are largely unpredictable. Thus, for the sake of assessing trajectory feasibility (*flyability*) at planning time, the interest is not to predict local atmospheric conditions and phenomena very accurately (which is impossible), but rather to be able to bound such effects for the given operational scenario based on a few statistical figures characterizing the average and maximum levels of turbulence or gusts magnitude and frequency. Hence, the uncertainty associated with how adverse local wind effects can be bounded results critical to safety, as it may drive the (wrong) decision to clear a trajectory for execution, which subsequently proves unsafe for the given vehicle. How local wind effects affect an aerial vehicle is largely vehicle-specific, but also depends on the specific phase of the flight. In effect, at higher altitudes, speeds or in certain configurations of engine regimes, the susceptibility to such effects may be lower than during takeoff, landing, operations at low speeds or close to buildings or obstacles. Thus, the ability to bound local wind effects in the vicinity of takeoff and landing pads (e.g. in urban VTOL operations) results critical to drive operational decisions on when such locations are available and when they are not, which has to be determined at planning time (based on forecasts) as well as continuously reassessed during execution (based on nowcasts, or local sensors, or a combination of both). In high traffic environments, the fact that a takeoff/landing location may suddenly become unavailable due to rapidly changing atmospheric conditions would require the *traffic management* services (planning and execution) to divert and reorganize the traffic flows on the go.

The approach of predicting/estimating average values and bounding the local deviations with regards to such average so as to support robust operational decisions can be applied to atmospheric conditions others than wind, like temperature, pressure, icing, precipitation, visibility, convective phenomena and even lightning.

Table 3 summarizes the meteorological information invariably needed to support drone operations in general. Ultimately, the objective of meteorological information is twofold: 1) anticipate the zones of an airspace that are propitious for the optimal drone operation and 2) avoid those that represent unacceptable safety risk or significant risk of mission failure because of adverse weather.

Weather information aspects	**Data representation**	**Geographical scale**	**Timeframe**	**Purposes**
Weather information provider ID	Unique SP identifier	Local & micro	Planning, execution & post-flight	Operational (mission, flight & traffic) Administrative (e.g. historical weather data)
Look-ahead type	Forecast/nowcast			
Data generation time	Date and time in standard format			
Applicability timeframe	Forecast period			
Temperature	{4D distribution}	Local		
Pressure	{4D distribution}			
Icing	{4D distribution}			
Visibility	{4D distribution}			
Precipitation	{4D distribution}			
Convective precipitation	{2D+t distribution}			
Lightning	{2D+t distribution}			
Average wind (u,v,w)	{4D distribution}	Local & micro		
Turbulence	{Statistical model}			
Gusts	{Statistical model}			
Thermals	{Statistical model}			
Forecast/nowcast uncertainties	Solution-specific			
Warning and alerts	Notice message; {airspace affected}			

Table 3: Summary of relevant meteorological information needed for drone operations

Regarding avoidance of adverse weather, the weather services might be required to issue operational *warnings* or *alerts* about unexpected or severe weather conditions.

3.4 System (UAS)

To facilitate a common understanding of the capabilities of operated drones, in regard to regulative aspects, as well as for flight and traffic planning and execution purposes, the relevant technical characteristics of all elements in the complete unmanned aerial system need to be known by U-Space actors[9] others than the drone operator itself (e.g. traffic management services, airspace

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[9] Some discrepancies may exist with the CORUS Concept of Operations for U-space [2] which considers that part of this information will be confidential as it is closely linked to the drone operators' business cases or to the drones' manufacturers. The availability of this information is not as relevant for the CORUS concept, since it considers drone operator the sole responsible of providing a consistent flight plan in line with the specifications of their missions and drones. Thus other U-space actors will not need to know the drone technical specifications.

authorities, etc.). This covers technical specifications, key airborne and ground components, software specifications and payload subsystems. Furthermore, operating conditions and critical performance aspects of the system, including the limits in which a drone can fulfil its mission are considered relevant system information as well.

All this information needs to be pulled from several sources: as an assumption, standardized specifications would be provided by manufacturers, the characterization of the UAS against a reasonably simple scheme of *capability levels* is developed by regulators and all diversions from standard configurations (e.g. payload, additional safety systems, etc.) are filed by the responsible operator. Same applies to the non-airborne system components as the ground control stations.

UAS aspects	**Data representation**	**Timeframe**	**Purposes**
UAS information provider ID	Unique SP identifier (alphanumeric code)	Planning, execution & post-flight	Operational Administrative
AV ID	Unique AV identifier (alphanumeric code)		
AV model	Manufacturer and model identifier		
AV type	CTOL, VTOL, etc.		
Propulsion characteristics Propulsion type Number of engines	 Glider/Electrical/Piston/Turbine/etc. 0,1,2,…		
AV Class (EASA/JARUS)	Lighter-than-air/Ax/Bx/Cx, etc.		
AV Size	Relevant AV dimensions		
Visual characteristics	Picture/description		
AV Maximum Takeoff Mass	Numeric value and units		
AV wake vortex category	Classifier		
Weather susceptibility category	{Dataset characterizing the susceptibilities of the UAS to different aspects of weather conditions}		
UAS airworthiness certificate	Certificate Designator		
UAS technical specifications	Matrix of tech specs designators		
AV performance characteristics	Tables		
CNS equipment Communication capabilities Navigation capabilities Surveillance capabilities	Tables		
Autopilot characteristics Contingency management capabilities	Tables		
Flight termination systems	Tables		
GCS characteristics Contingency planning capabilities	Tables		
Payload characteristics	Tables		
Other equipment	Lights, mission-communications, etc.		

UAS aspects	Data representation	Timeframe	Purposes
Maintenance status	Maintenance and technical inspection status data		
UAS capability ID	Alphanumeric code summarizing UAS capabilities		

Table 4: Summary of relevant UAS system characteristics

Table 4 presents a synopsis of the main aspects or categories of aspects that need to be known by U-Space about specific UAS instances, the details of which are largely still to be determined.

Several countries have already implemented their own national drone registries, however most of these seem to be tailored to meet current needs for small drone operations in VLOS. It remains to be seen how such systems can be scaled to large scale autonomous BVLOS/BRLOS operations, in both rural and urban environments.

Drone registry databases may though be subject to more stringent registry requirements than manned aircraft, given their highly diverse operating capabilities, sizes, velocities and onboard equipment. It may become necessary to classify drones based on a set of standardized *capability levels* which govern flight restrictions on drones depending on their operating environments. These capability levels might be derived from the UAS system data reflected in Table 4 either on a '*per model'* basis or, more specifically, '*per drone ID*'.

To safely manage large quantities of drones flying in piloted and autonomous mode, a centralized and supervised database for *drone operators registry and identification* will also be needed. This registry should encompass the essential information about drone operators qualified to operate drones in U-Space, namely:

Drone operator aspects	Data representation	Timeframe	Purposes
Operator information provider ID	Unique SP identifier (alphanumeric code)		
Operator ID	Unique operator identifier (alphanumeric code)	Planning, execution & post-flight	Operational, Administrative
Operator contact info	IP address, phone, e-mail, etc.		
Operator type	private, commercial, state, etc.		
PIC ID	Unique alphanumeric code		
PIC contact info	IP address, phone, e-mail, etc.		
PIC license type(s)	List of valid PIC licenses		
Type of activity	Declared purpose of the activity		
Insurance	Type and status of insurance coverage		

Table 5: Summary of relevant drone operator aspects

It can be expected that drone operators shall be subject to regulations analogous to those that apply to manned aviation operators. In manned aviation, an *Air Operator Certificate* (AOC) is required to perform commercial activities such as aerial surveying, aerial spotting, agricultural operations, aerial photography, aerial advertising, firefighting, air ambulance, flight training, charter and public transport [16]. In terms of information requirements, no drastic changes are expected with respect to the existing approach in manned aviation [16].

A similar approach to that of operator certification could be applied to *drone pilot database*. Drone pilots are registered under the same structure as pilots of manned aviation, just under a different identification, which might be as simple as adding one or more types of *'Remote Pilot License'* to the list of available licenses [17][18].

3.5 Communications

As it applies to all aerial vehicles in the current aviation system, all UAS operating within U-Space shall have to feature a communications solution enabling the exchange of operational information with U-Space. Several key differences with manned aviation though drive special needs as it comes to drone operations, namely:

- Drone PICs no longer sit onboard the AV; they are located remotely –most likely in a ground location which may not be fixed (e.g. deployable GCS or onboard another ground, maritime or aerial vehicle)
- U-Space is assumed to be natively realized through a number of services not likely to be geographically co-located
- U-Space traffic management services in charge of supporting traffic planning and execution are assumed to work automatically, i.e. without requiring human operators in-the-loop such as the ATC officers (ATCOs) in manned aviation
- In the longer term –or earlier in certain environments, drones are assumed to reach high levels of autonomy to the point that might make human PICs in-the-loop no longer needed

Figure 3 schematically represents the communication needs of drones in view of known communication approaches in place in ATM and the considerations above.

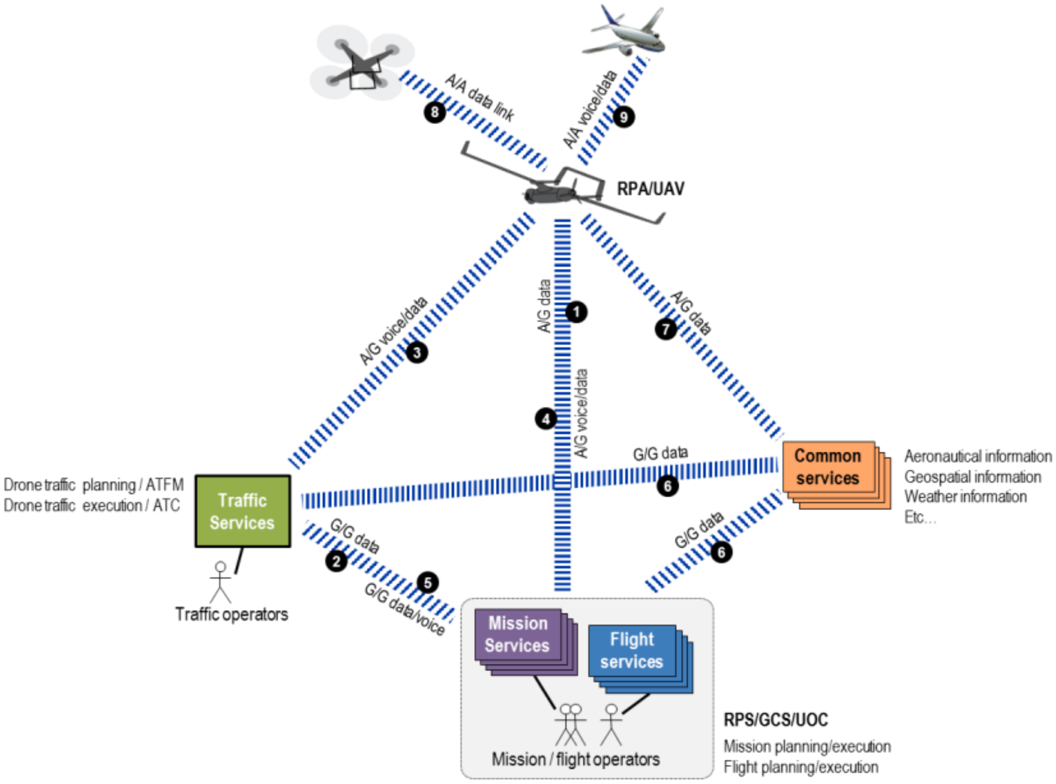

Figure 3: Schematics of relevant drone communication needs

In effect, from the perspective of the logical connection paths –i.e. the needs to connect Airborne (A) and ground (G) elements among them regardless the physical solution used to actually implement such connection (e.g. optic-fibre/cable or aerial/satellite radio links), the following nine communication needs can be identified:

1) The obvious Air/Ground (A/G) command and control (C2) or, more precisely, *Command and Non-PayLoad Communications* (CNPLC) connecting the *Remotely Piloted Aircraft* (RPA) or UAV with its *Remote Pilot Station* (RPS) or GCS for the exchange of *telemetry* and *telecommand* information[10]
2) The Ground/Ground (G/G) data connection between the GCS and U-Space *traffic management services* through which relevant mission information in addition to critical flight and traffic planning and execution information can be exchanged

If the UAV needs to operate outside U-Space, it shall need to interact with ATM using standard ATC voice and/or ATS data communications infrastructure, which entails:

3) Standard ATC/ATS A/G voice and data communications –which implies that the UAV would need to feature the corresponding standard onboard communications equipment

However, since the PIC and its supporting GCS are located remotely:

4) The ATC/ATS A/G voice and data would need to be relayed over the CNPLC link. This might introduce latencies possibly impacting PIC and controller workloads
5) Alternatively (or, more likely, in addition) to the combination of 3) and 4) –for redundancy purposes, ATC/ATS A/G voice and data might be exchanged between the ATM system and the GCS via a G/G link. This would require adapting legacy ATC/ATS infrastructures to properly manage both communications paths.

In any case, mission, flight and traffic services would need to exchange data with a variety of other U-Space services (e.g. *aeronautical*, *geospatial*, *weather*, etc.), which includes both:

6) G/G data exchange between such *common services*, *traffic management services* and the ground piece of *mission and flight management services*
7) A/G data exchange between such *common services* and the airborne piece of *mission and flight execution services*

Finally, if the UAV operates in a dense traffic environment, it is likely that it has to cooperatively broadcast its identity, position and intent (e.g. through ADS-B), as well as receive analogous data from the other AVs operating in its vicinity. Contingency situations might need to also be reported to the vehicles nearby. In particular Loss-of-Separation (LoS) contingencies may require coordinated collision avoidance manoeuvres between the concerned AVs (like TCAS [19] in manned aviation). To that end:

8) An A/A data connection is required for the cooperative exchange of data relevant to *airborne surveillance* (traffic detection) and *collision avoidance*, as well as to alert surrounding traffic about contingency/emergency situations

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[10] The A/G data connection between the UAV and the GCS to exchange mission-specific information is intentionally left out of the scope of this document as it is irrelevant to U-Space

Again, in case that the UAV needs to operate in controlled airspace, analogous needs apply, though the implementation shall have to follow manned aviation standards. In this case, in addition to data, the voice heard by the UAV in the applicable ATC or ATS frequency at its location would be relevant to the PIC for situational awareness and, conversely, the conversation between the remote PIC and ATC would be relevant to the surrounding manned traffic. Thus, it should be relayed through the CNPLC link. In this case, this leads to the need of:

9) A/A voice and data connections to, respectively, relay ATC/ATS voice between the UAV and the PIC, and implement the cooperative traffic surveillance (e.g. ADS-B) and collision avoidance (e.g. TCAS or ACAS-X [20]) capabilities required in the given airspace

For the sake of simplicity, in the previous discussion, it has been assumed that mission and flight planning and execution services are co-located as part of the UAS GCS or UAS Operations Center (UOC) and that so are traffic planning and execution services. If it is not the case, additional G/G communication needs might have to be considered.

In view of the communication needs identified, and bearing in mind the multiplicities of U-Space services and, especially, of UAS instances, a net-centric service-oriented information management approach analogous to the SWIM (System-Wide Information Management) [5] concept adopted in ATM is envisioned to become necessary to handle all the complexity implied. Hence, although new communication technologies have emerged after SWIM started its development that should be regarded, many of the requirements, design principles and even specific solutions adopted in SWIM should be leveraged in U-Space to avoid ‘entirely’ reinventing the wheel.

3.6 Navigation

With no exception, all UAS must feature a *navigation function* that provides the *navigation information*, essential to guide and control the motion of the AV so as to execute its trajectory.

As an integral part of the GNC (Guidance, Navigation and Control) system, the navigation function together with the *guidance function* continuously produce a *reference* (desired) *AV motion state* that, subsequently, the *flight control function* tries to reach by properly acting on the AV flight control actuators. The way in which guidance, navigation and control functions work together to execute the AV trajectory varies amply across GNC solutions, depending upon the paradigm adopted for each of the three constitutive pieces, which may be different for different aspects of the AV motion state.

Ideally, the navigation function provides an observation of certain aspects of the AV state that need to be controlled at a time against the corresponding references (e.g. 2D position, altitude and airspeed), the guidance function provides such references and the control function, fed with both the observed and reference states, determines how to act on the flight controls so as to cancel the difference between them. In practice, a great deal of casuistry may appear. Sometimes the reference state is implicit within the navigation solution (e.g. ILS or VOR radial following), so what the navigation function provides is not an observation of an actual aspect of the AV state of interest, but a measure of the error between it and the reference one, which makes the job of the guidance function trivial. Sometimes, the guidance function focuses on designing a guidance law to drive the error between observed and reference states down to acceptable limits (e.g. ILS LOC or GS or VOR radial capture), the flight control function thus trivially following such a law. In some other cases (e.g. altitude, speed or course holding), the reference aspect of interest of the AV is explicit, which, again, makes the guidance function trivial. Yet in some other cases (e.g.2D/3D path following) the guidance reference (i.e. the trajectory geometry) has to be (non-trivially) materialized through synthetic computation rather than signal sensing.

Since the introduction of the concept of *Area Navigation* [33] and GNSS, navigation solutions in manned aviation tend to adopt the PVT (Position, Velocity and Time) approach, which enables the so-called *waypoint-based navigation* or absolute navigation. This has led to the tendency of adopting 2D/3D geometries described in terms of discrete sequences of 2D/3D waypoints as the trajectory reference in modern flight plans. However, again, a great disparity of GNC approaches can be found as related to the specific 'recipes' of guidance and control modes applied to execute the exact same waypoint-based 2D or 3D trajectory reference, which gives rise to large unpredictability issues. In an attempt to address these issues, which hamper the introduction of high levels of trajectory management automation in dense traffic environments, ATM modernization initiatives like SESAR and NextGen advocate for the adoption of the concept of *4D trajectory*, where, in addition to a 3D trajectory, the flight plan also commits to a specific timing schedule.

As of today, most UAS feature PVT navigation solutions augmented with inertial (INS), and possibly, magnetic measurements. In general, there is high dependency of GNSS for safe drone flight, although low-altitude environments are more susceptible to GNSS outages to satellite signal blockage by trees and buildings. Methods of mitigation such outage will consider alternate navigation sources like optimal matching of terrain data to provide a cross check of the estimated position. Although the introduction of these mitigation measures could be less urgent when flying far from manned aviation, operations within controlled airspace could require them.

Fixed-wing UAS typically also feature air data measurements as part of their navigation solution, which allow them to sense airspeed, pressure, outside air temperature (OAT) and instantaneous wind at the local AV position. Some fixed-wing UAS may also integrate angle-of-attack (AOA) and angle-of-sideslip (AOS) sensors.

The PVT solution most widely adopted in many small UAS is typically provided by a GNSS sensor and the inertial measurements are provided by low-cost solid-state accelerometers ad gyros, Extended Kalman Filter (EKF) or analogous filters being the most common fusion approaches implemented.

This works well as long as GNSS behaves as expected, since it allows containing the considerably large drift inherent to MEMS-type accelerometers and gyros. Nonetheless, when GNSS becomes unavailable, the uncontained drift makes the state estimator based on this approach useless in a matter of seconds or minutes –depending on the size and performance of the AV, sensor quality and sensor fusion approach, and, thus, the navigation function is lost. In this situation, especially if the flight control capabilities are limited to only fly waypoints (i.e. absolute navigation), the UAS is no longer able to follow the intended trajectory nor any contingency trajectory whatsoever. Furthermore, in loss navigation, geofencing mechanisms no longer work and so happens with dependent surveillance means, such as ADS-B and telemetry-derived traffic surveillance.

This critical dependency on GNSS signals for navigation represents a major obstacle for UAS operations in general and, in particular, in civilian ATM environments, because GNSS does not fulfil the performance requirements (in terms of *accuracy*, *integrity*, *availability* and *continuity-of-service*) to serve as *single means navigation system* in civil aviation [77], plus it is susceptible to jamming, spoofing and multipath issues[11]. Besides the direct impact in navigation, *Loss-of-GPS* (LoG) can further cause the concurrence of LoL in RLOS implementations of the CNPLC link, where the ground segment typically relies on a directive antenna continuously pointing to the AV position, the antenna pointing mechanism using the AV position extracted from the telemetry.

Given the navigation solution typically adopted by small/medium[12] legacy UAS, the only way to maintain acceptable navigation performance when GNSS becomes unavailable is through exploiting additional sources of navigation information, which will likely include non-conventional navigation means.

Navigation information aspects	**Data representation**	**Purposes**	**Timeframe**
Position 2D	2D coordinates, reference	mission execution flight execution contingency management	Execution & post-flight
Altitude	Value, units		
Altitude reference	Geometric/pressure, AGL/ASL, QNH/QFE		
Ground speed	Magnitude, direction, reference, units		
Time	Magnitude, format/units, reference		
Vertical speed	Magnitude, reference, units		
Acceleration	Vector, reference units		
Attitude (pitch, roll, yaw)	Vector, reference units		
Angular speed (pitch/roll/yaw rates)	Vector, reference units		
Angular acceleration	Vector, reference units		
Course	Magnitude		
Course reference	Magnetic/geographic, bearing/heading		
Turn rate	Magnitude, reference, units		
Airspeed	Magnitude, units		
Airspeed reference	IAS/EAS/TAS/MACH		
Angle-of-attack	Magnitude, units		
Angle-of-sideslip	Magnitude, units		
Local wind (u,v,w)	Vector, reference, units	mission/flight execution, weather	
Local pressure	Magnitude, units		
Local temperature	Magnitude, units		

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[11] GPS-denied is also a major issue in military or security applications because of the increasing spread of counter-measures such as intentional jamming and spoofing (GPS-contested), as well as in indoor operations of micro-UAS, because of possible complete unavailability of GPS signal.

[12] For larger UAS that can afford *navigation-grade* INS solutions GNSS inoperative is not such a big deal, as INS operating stand-alone might sustain acceptable navigation performance for enough time to at least safely ground the AV.

Navigation information aspects	Data representation	Purposes	Timeframe
NAV sources	Code describing the NAV sources used	contingency management	Planning, execution & post-flight
Accuracy	Miscellaneous accuracy measures		
Integrity	Probability function, time to alarm [s]		
Availability of service	Probability function	contingency planning	Planning & post-flight
Continuity of service	Probability function		

Table 6: Summary of relevant navigation information needed for drone operations

Consequently, two challenges appear: i) what is to be considered 'acceptable navigation performance' as it relates to UAS is still to be defined, and ii) such performance will depend on the navigation means adopted, which will likely be subject to considerable heterogeneity. The capability-based approach that needs to be developed to articulate safe UAS operations in different contexts will need to pay special attention to these issues.

Anyhow, navigation capabilities will be defined in terms of the navigation information required to support drone operations, which in general may include a more or less extensive subset of the navigation information aspects enumerated in Table 6.

3.7 Surveillance

In manned aviation, the term 'surveillance' may refer to several functions, all of them related to the notion of detecting something that may represent a hazard for the AVs operating so it can be can be safely avoided. The surveillance categories typically considered in manned aviation include *terrain*, *weather* and *traffic* surveillance.

Although terrain and obstacle clearance in manned aviation is guaranteed at procedure design time through adopting very conservative altitude margins over known terrain and obstacles, as a safety net to prevent CFIT (Controlled Flight Into Terrain) accidents, many commercial aircraft feature a radar altimeter or a more or less sophisticated Terrain Awareness Warning System (TAWS) [21] such as GPWS (Ground Proximity Warning System) [22] or Enhanced GPWS (EGPWS) [23]. As for UAS, depending on the intended operational context and altitudes, either one of the two approaches – i.e. planning-time based on data or execution-time based on an on-board capability or both may be necessary to guarantee terrain and obstacle clearance.

For drones having to operate much closer to the terrain and obstacles than typical manned AVs would do, new challenges appear, namely: i) the terrain and its salient features such as buildings, trees, etc., need to be known with much higher resolution, and ii) the man-made obstacles relevant to drone operations, such as antennas, aerial cables, cranes and new buildings are more numerous and tend to be more dynamic than those relevant to manned aviation. In this case, two possible solutions concerning terrain and obstacle surveillance information needs are envisaged:

1) An online service providing safe separation from terrain and obstacles in a detailed way, considering lateral in addition to vertical separation, as well as accounting for drone navigation performance and the more dynamic nature of the obstacles. Such a service would rely on accurate and current *geospatial information* (§3.2) to provide a 'synthetic surface' not to be trespassed ensuring safe separation, customized to a particular environment (e.g. a city) or, furthermore, to a particular drone operation.

2) A low-SWAP onboard terrain and obstacle detection system. Some drone equipment manufacturers have already developed solutions along this idea based on artificial vision, LiDAR or ultrasounds [24], whose performances for the time being limit their use to short range and low speed (mostly near hovering) applications such as inspections or indoor. Assuming that a significant number of drones might be operating in the future equipped with a solution like this, they might significantly contribute to maintain current and accurate drone obstacle.

Regarding weather surveillance, many commercial aircraft feature Weather Radar Systems (WRS) [25] and/or Predictive Wind Shear (PWS) solutions [27], intended to detect and avoid severe weather conditions, which at the scale of manned AVs are storms, convective weather phenomena at regional or local scale and other local phenomena like wind shear. Wind shear has also been surveyed on the ground at airport locations [26]. At the scale of small and medium sized drones, more local and even micro-scale weather phenomena need to be accounted for to guarantee their safe operation. Again, two possible approaches concerning weather surveillance information needs are envisaged:

3) An online service providing safe separation from local and micro-scale adverse weather conditions as related to drone operations. The service would rely on weather nowcast/forecast information (§3.3) to confine the airspace volumes where a high probability of encountering unsafe weather conditions is found. Such volumes not to be occupied by drones below a certain category of susceptibility to severe weather or wind phenomena would be continuously updated, tailored to a particular environment (e.g. a city) and drone *weather/wind susceptibility category*.

4) A low-SWAP onboard weather/wind surveillance solution (e.g. based on IR, radar, etc.). To our knowledge, no such solution has yet been attempted.

Regarding traffic, in manned aviation standardized traffic surveillance means are in place to help air traffic controllers and pilots maintain separation. *Ground traffic surveillance* integrates AV state estimates possibly coming from both cooperative (SSR [28], ADS-B/out [29], SSR-based multilateration [30]) and non-cooperative (PSR) sources to generate the traffic picture used by ATC. Typical ground surveillance data include the AV 2D position, ground speed and a measure of its altitude plus the AV ID –if correlated with the AV flight plan, as well as other data such as Mode-C altitude, rate of climb/descent, etc. –when reported by the AV. With the exception of Air-to-Air radar –which few civil aircraft feature, all *airborne traffic surveillance* means are cooperative to some extent. The simplest versions of them just rely on TCAS to estimate the positions of the surrounding AVs relative to the ownship. More advanced airborne traffic surveillance means include ADS-B/in and TIS-B [32], which cooperatively acquire more detailed and accurate traffic data as reported by, respectively, the surrounding AVs using ADS-B/out and the ATS –when an ATS datalink environment supplying TIS-B is in place.

As it relates to UAS, neither ground surveillance of drone traffic to ATC nor airborne traffic surveillance of any kind to the UAS remote pilot is guaranteed using standard surveillance means. Only recently, SSR transponders and ADS-B equipment are becoming available at the SWAP scale that would fit relatively small UAS, however SWAP and emission power limitations and the low flight altitudes typically flown by drones make them a limited choice in many UAS applications. For the time being, the only means for UTM services to acquire drone traffic surveillance is through cooperative reporting by the corresponding GCS via Internet based on the drone telemetry data.

In view of this, the following traffic surveillance information needs are identified, which will require that specific traffic surveillance capabilities/services are developed.

With regard to airborne traffic surveillance:

5) How to enable manned AVs acquiring UAS traffic operating nearby
6) How to enable UAS acquiring both manned traffic and UAS traffic operating nearby

Regarding ground traffic surveillance:

7) How to enable UTC acquiring both manned traffic and UAS traffic
8) How to enable ATC acquiring UAS traffic

Of the traffic surveillance needs identified, U-Space is concerned with 5), 6) and 7), whereas traditional manned aviation users are concerned with 5) and 8).

Table 7 provides more comprehensive details on the relevant traffic surveillance information envisaged to be needed to support drone operations.

Traffic surveillance aspect	Data representation	Purposes	Timeframe
Surveillance SP ID	Unique SP identifier (alphanumeric code)	flight execution, traffic execution, contingency management	Planning & post-flight
Flight ID	Unique flight identifier (alphanumeric code) or assigned ID		
Position 2D	2D coordinates, reference		
Course	Magnitude		
Course reference	Magnetic/geographic, bearing/heading		
Ground speed	Magnitude, direction, reference, units		
Airspeed	Magnitude, units		
Airspeed reference	IAS/EAS/TAS/MACH		
Turn rate	Magnitude, reference, units		
Altitude	Value, units		
Altitude reference	Geometric/pressure, AGL/ASL, QNH/QFE		
Vertical speed	Magnitude, reference, units		
Time	Magnitude, format/units, reference		
Trajectory intent	{Data structure formally describing the trajectory intent}		
Containment volume	{Data structure formally describing the 4D containment volume of the intended trajectory}		
SUR sources	Code describing the surveillance sources used	contingency management	Planning, execution & post-flight
Delivery time	Probability function		
Accuracy	Miscellaneous accuracy measures		
Integrity	Probability function, time to alarm [s]		
Availability of service	Probability function	contingency planning	Planning & post-flight
Continuity of service	Probability function		

Table 7: Summary of relevant traffic surveillance information needed for drone operations

3.8 Flight

Flight data is related to information that is indispensable to describe, manage, and control the safe movement of AV. Predominately, this covers the *planning* and *management* of nominal and off-nominal flight events as well as their recording.

Flight planning information is necessary for future drone applications that foresee a high degree of automation and precision in their operations. In particular, it is pivotal to enable a safe, efficient and ordered use of the airspace. Currently, most drone autopilots are fitted with waypoint-based GNC systems. Using this approach, it is possible to further specify drone missions that contain specific flight patterns, which in turn can be useful for various applications like recognition and search & rescue. However, as integration of UAS with manned aviation moves forward in the coming years, it is important to retain procedures from manned aviation as much as possible in order to facilitate interoperability. Flight Management Systems (FMS) found in most commercial aircraft today are the pilot’s primary interface for flight planning operations. These systems utilize standard performance-based RNAV instrument procedures (RNP) [33] for defining the specific path to be followed by an aircraft.

Trajectory aspect	Casuistry	Data representation	Implications
2D geometry (lateral path)	Earth-fixed	Sequence of 2D waypoints or lateral geometry primitives (e.g. straight legs and arcs, splines)	2D geometry known at planning time with relatively low degree of uncertainty depending on the primitives used. This allows ensuring avoidance of fixed 2D NFZs at planning time
	Wind-dependent	Bank or course holding targets (e.g. ATC vectors)	2D geometry depends on the wind experienced –larger uncertainty and thus larger lateral separation minima required cross-track
	Mission-driven	Not available at planning time (e.g. inspections, moving target following)	Large uncertainty; bounding it may require large lateral separation minima cross-track
Altitude profile (vertical path)	Earth-fixed	Geometric altitude AGL specified for each 2D waypoint or vertical geometry primitives (e.g. geometric path angle)	3D geometry known at planning time with relatively low degree of uncertainty depending on the primitives used. This allows ensuring terrain and obstacle clearance as well as avoidance of fixed 3D NFZs at planning time
	Pressure, wind or performance-dependent	Altitude expressed in terms of pressure altitude (altitude reference needed) and/or climb/descent primitives in terms of airspeed, vertical speed, aerodynamic path angle or throttle control	Geometric altitude depends on atmospheric conditions experienced and/or vehicle performances –larger uncertainty and thus larger vertical separation minima required
	Mission-driven	Not available at planning time	Large uncertainty; bounding it may require large vertical separation minima
Timing	Time control	Controlled Time of Arrival (CTA) constraints specified for each 2D waypoint or ground speed primitives	4D trajectory (i.e. 3D geometry and timing) known at planning time with relatively low degree of uncertainty depending on the primitives used and

Trajectory aspect	Casuistry	Data representation	Implications
			wind uncertainty.
	Pressure, wind or performance-dependent	Airspeed or throttle control holding targets (e.g. CAS/MACH)	Timing depends on atmospheric conditions experienced and/or vehicle performances –larger uncertainty and thus larger lateral separation minima required along-track
	Mission-driven	Not available at planning time	Large uncertainty; bounding it may require large lateral separation minima along-track

Table 8: Summary of relevant AV trajectory modelling aspects and their operational implications

The accuracy and level of detail in the definition of a drone flight trajectory (e.g. in terms of a sequence of 2D, 3D or 4D waypoints) have a critical impact in airspace capacity and efficiency, since more precise definitions of drone trajectories in space and time imply smaller uncertainty about the drone position over time, lower separation minima to cope with such uncertainty, more strategic and robust traffic management decisions, less chances to experience losses of separation and, thus less tactical interventions needed to fix them.

Table 8 provides a summary of the casuistry that can be found when planning AV trajectories using different types of trajectory modeling primitives and their operational implications in terms of separation minima.

Most UAS use Earth-fixed 2D waypoints to capture the lateral path of the trajectory at planning time, whenever it is not mission-dependent. Nevertheless, large heterogeneity can be found in how legacy UAS determine altitude and timing profiles. In many cases the flight plan only loosely determines the altitude profile and little or no information at all is captured that can determine the timing profile beforehand.

Two important consequences can be drawn from the discussion above from the *traffic/separation* point of view:

i) Even though the 2D geometry is reasonably well captured in general, which allows accurate geofencing, both the lateral separation along-track and the vertical separation may need to be considerably large to cope with the corresponding uncertainties. This has to be taken into consideration by traffic management services when trajectory interactions (conflicts) can occur.

ii) Mission-driven trajectories may either require extremely large uncertainty buffers –i.e. separation minima, or a geofencing mechanism that the UAS complies with, which dynamically ensures that the UAV never exits the assigned volume of airspace circumscribing the mission.

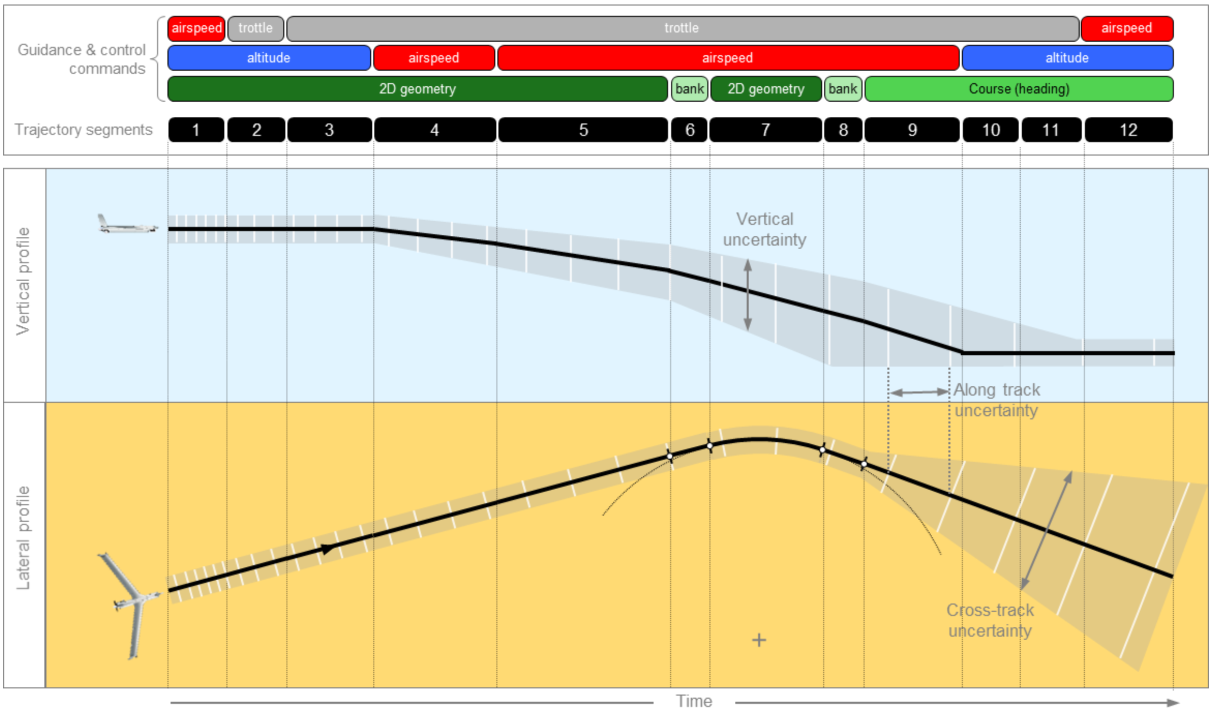

Figure 4: Sample representation of AV trajectory uncertainty vs. the trajectory recipe applied

Separation minima, thus, depend on the flight planning approach adopted as well as on the type of mission. Furthermore, they also depend on the UAV navigation accuracy and on the specific way in which its internal guidance and control system fills in the gap to close the degrees of freedom left undefined in the flight plan. This is reflected in Figure 4, which shows a nominal trajectory (black bold line) surrounded by grey volumes that represent the uncertainty of the AV 4D positions. This uncertainty varies considerably along the trajectory depending on the guidance and control 'recipe' – formally so-called *aircraft intent* [34], exerted in all the 3 control degrees of freedom of the AV motion, which are not typically captured in full detail by the flight plan.

Another important consideration from the point of view of the of the individual *flight* being planned is that trajectory definition uncertainty may have important safety implications, as it entails estimates of the fuel/energy to be consumed – and thus, the reserves needed, flight altitudes – and thus, terrain and obstacle clearance, and assumed atmospheric conditions – which may experience significant deviations.

Besides planning the nominal flight trajectory, it is crucial to anticipate any foreseeable off-nominal situation such as in-flight contingencies that can compromise safety and thoroughly prepare contingency management procedures to effectively cope with them. In addition to in-flight contingencies like *loss-of-separation* (LoS) or *loss-of-engine/energy* (LoE), which do also affect manned AVs, UAVs, because of their nature, are subject to new ones such as *loss-of-link* (LoL), and *loss-of-GNSS* (LoG), as well as more prone to *loss-of-control* (LoC).

Because of their safety-critical nature, in-flight contingencies should be approached more comprehensively than they are treated in today's legacy UAS. Such a comprehensive approach should consider all concerned actors having a say in the UAS operations, i.e. mission, flight and traffic management systems, as well as address the contingency holistically, from

i) How to fix the deficiencies associated to current CNS infrastructures and equipment that originate them or prevent them to be adequately managed, through

ii) What can be done at planning time to prevent contingencies or, at least, facilitate preparation to manage them, to, ultimately,

iii) How to safely cope with them once they happen in order to mitigate their consequences.

Complementarily to nominal *flight planning* and *flight management* functions, *contingency planning* and *contingency management* functions are respectively envisaged to cope with issues ii) and iii) above.

Finally, as long as the flight is concerned, all flight-related information relevant to safety, security or privacy would need to be continuously recorded by the drone operator during the operation execution as evidence in case of the corresponding investigations, as well as to create a base of experimental data from which to learn how to improve operations.

Table 9 below summarizes the relevant information that a formal drone flight plan should capture in general.

Flight plan data field	**Data representation**
Flight ID	Unique flight identifier (alphanumeric code)
Change number	Flight plan change number: 1 (first request), 2, 3, ...
Mission ID	Unique identifier of the mission that the flight belongs to
Operation category	EASA – open/specific/certified or similar simple classification
Range category	VLOS/BVLOS/RLOS/BRLOS
Autonomy category	Category of flight management autonomy: from remotely piloted to fully autonomous
AV ID	Unique AV identifier (alphanumeric code)
Priority category	Level of priority assigned to the flight as per the mission plan
U-Space services required	{List of U-Space services required to perform the operation}
Departure location	Drone-port ID or geographical coordinates
Departure time slot	Date and time in standard format (e.g. UTC) [second-accuracy] plus allowable delay
Arrival location	Drone-port ID or geographical coordinates
Estimated time of arrival	Date and time in standard format (e.g. UTC) [second-accuracy]
AV trajectory	{Data structure formally describing the trajectory to be flown}
Containment volume	{Data structure formally describing the 4D volume containing AV position uncertainty}
Contingency plan	{Data structure formally describing the contingency plan}
Confidentiality level	Level of confidentiality applicable to the flight data (plan and records)
Requestor's digital signature	Digital signature of the requested flight plan by the requesting operator
Approving UTM	Unique ID of the UTM traffic planning service approving the flight plan
Approver's digital signature	Digital signatures of the approving UTM service
Pilot ID	Unique ID of the PIC assigned to the flight

Flight plan data field	**Data representation**
Pilot signature	Digital signature of the assigned PIC
Status	Requested > pending > valid/invalid[13] > approved/rejected > withdrawn > completed

Table 9: Summary of relevant drone flight plan information

3.9 Traffic

When more than one UAV or UAVs and manned AVs may operate concurrently in the same airspace, potential traffic issues come into scene.

From the *tactical* stand point (i.e. at execution time), especially in low density non-converging traffic scenarios, drone traffic issues might be relatively easy to solve through well-known traffic separation patterns (e.g. based on altitude, course or speed changes) similar to the ones routinely applied in manned aviation by trained ATC controllers. Replicating a human-centered approach to ensure safe UAS separation would, however, make commercial UAS applications unaffordable. Thus, a high level of automation (ideally, *full automation*) is paramount to be achieved by an equivalent *UAS Traffic Control* (UTC) service (§4.9.3). UTC automation involves automated *separation assurance* – which underlies the problem of *conflict detection and resolution*, as well as *traffic merging, sequencing and scheduling* for the more complex scenarios where converging traffic occurs.

In simple terms, the job of a UTC service is to ensure that:

i) Each UAV operating under its responsibility is always surrounded by a well-defined volume of airspace that is appropriately cleared from traffic

ii) All the protection volumes corresponding to all UAVs operating in a certain airspace region can be directed as close to each other as possible (safe separation should never result compromised), if needed, to enable as much capacity as possible

To do its work efficiently, UTC would ideally need to rely on some sort of prediction of the AV trajectory so it can anticipate potential losses of separation – *traffic conflicts*, and intervene accordingly to inhibit them from developing into actual separation infringement events. Four cases are envisaged, which may require different separation provision:

1) The AV has 4D navigation capabilities –i.e. can accurately follow a 4D trajectory in space and time. In this case, the 4D volume bounding the uncertainty associated with the prediction of the AV 4D position could be described by any of the primitives shown in Figure 5.

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[13] For flights that require a remote PIC in-the-loop (i.e. not fully autonomous), the flight plan might requested by the drone operator might be reviewed by the concerned UTM service and declared *'valid'*, however it would not be declared 'approved' by the UTM service until it has been signed by assigned PIC

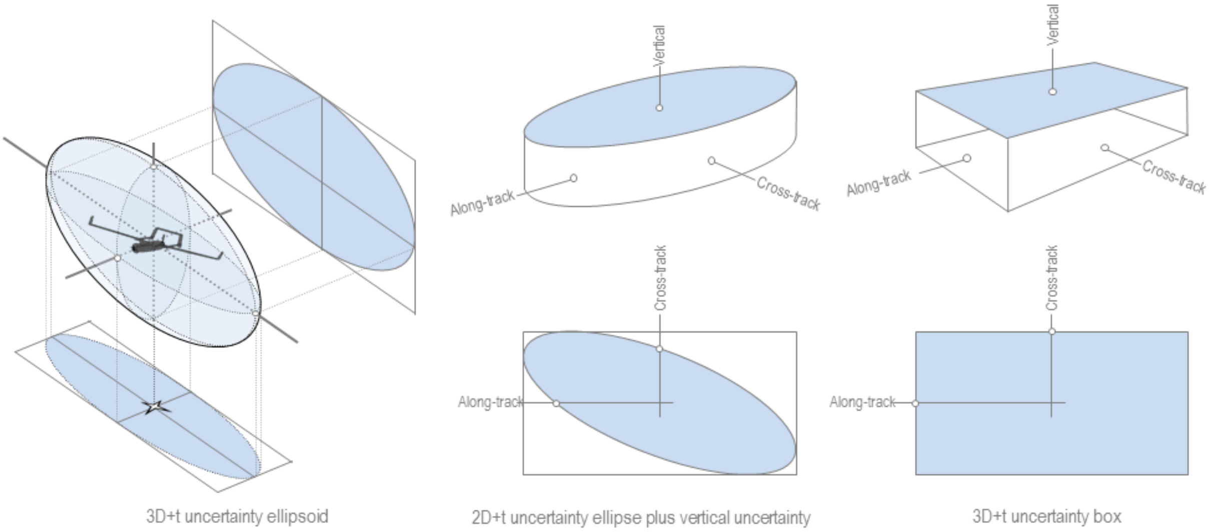

Figure 5: Representative 4D primitives to bound AV position uncertainty

2) The AV has 3D navigation capabilities –i.e. can accurately follow a 3D trajectory (the trajectory geometry), but cannot guarantee a required level of accuracy in its timing[14]. In that case, the predicted volume of uncertainty of the AV position needs to cover the whole trajectory segment being considered by UTC to ensure separation at a given time. As represented in Figure 6, the 4D uncertainty volume becomes a 3D volume which is the volume generated by the notional (unknown) 4D volume over the time interval considered.

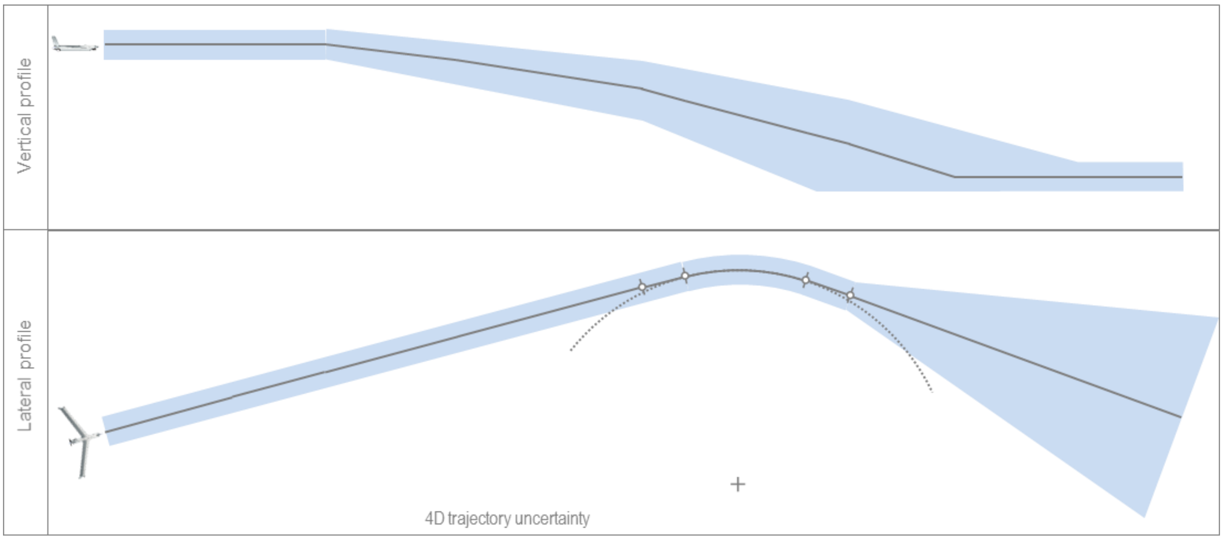

Figure 6: Representative 3D volume of AV position uncertainty along its predicted trajectory

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[14] Among the many reasons why timing accuracy may not be guaranteed when executing a trajectory, a major one is the uncertainty in the departure time. In effect, if traffic management services admit that the *departure time slot* of a planned UAS flight can be large –i.e. gives freedom to the drone to depart at any time within a large time interval, such time interval will directly go into uncertainty about the timing of the trajectory.

3) The trajectory is too complex or mission-driven, though it can be enclosed within a static 3D geofence in its entirety. As represented in Figure 7, a geofencing primitive might be defined bounding the AV position uncertainty for the entire trajectory.

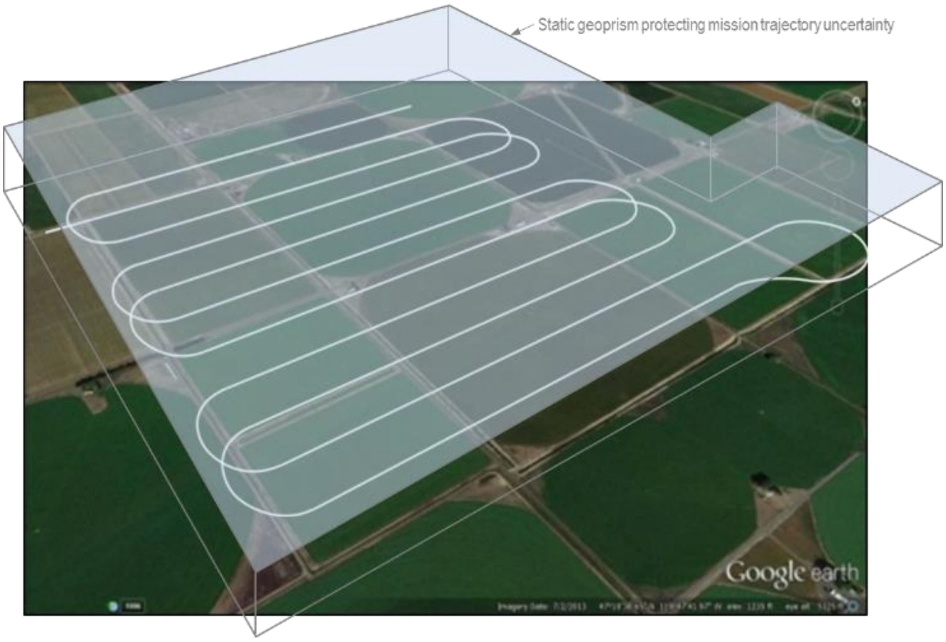

Figure 7: Representative 3D volume confining AV position along with its uncertainty

4) The trajectory is mission-driven, though certain degree of predictability can be derived from the mission to define a dynamic 3D volume –i.e., again a 4D volume, that bounds the uncertainty of the AV position. This case is illustrated in Figure 8 for the case of an AV tracking a ground moving target from within a certain distance. Although the motion of the AV is highly mission-driven, it can still be confined within a moving 'geocylinder' whose motion can be predicted to some extent through extrapolating the speed of the target being tracked.

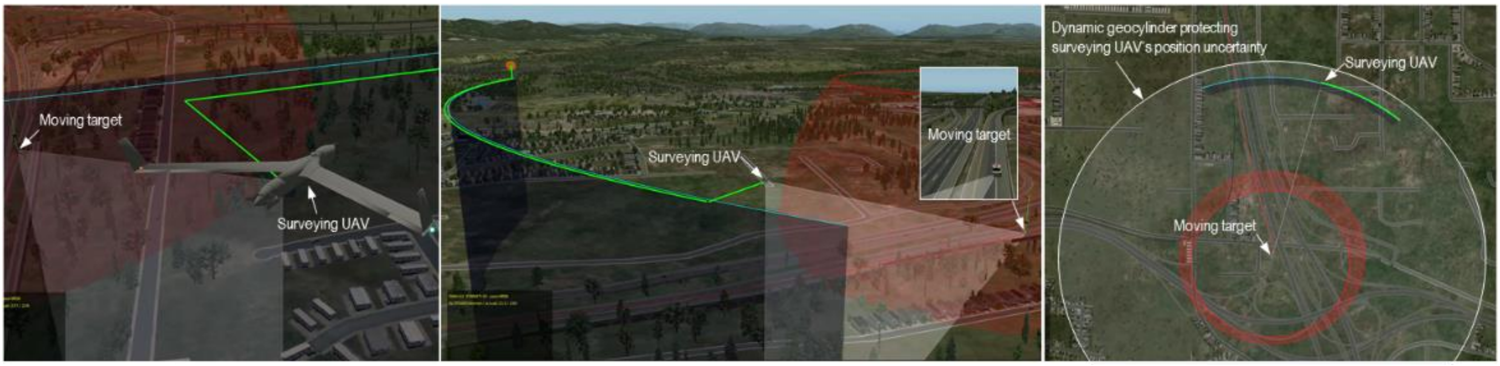

Figure 8: Representative 4D uncertainty volume of a mission-driven trajectory

Otherwise no strategic deconfliction can be performed at any timeframe and the deconfliction tasks could only be performed completely tactically, relying on just current AV positions as provided by the traffic surveillance capabilities.

In a way, this resembles the well-known *Tetris*® game [35]. How much traffic throughput can be handled in a given airspace depends on the shape and size of the individual protection volumes, their density and velocity of change, and the skills of the player (or equivalent automation algorithm) to compactly package them. As seen, the size, shape and position of the protection volume of a given UAV might or might not change over time. Thus, big, static protection volumes (geofences) would be simpler to deal with but detrimental to airspace capacity, while smaller, faster changing volumes would enable higher capacity but, consequently, entail higher complexity. What is the best approach to adopt in each case depends on many things, among them, how dynamic the mission trajectory to be flown by a given UAV needs to be, how accurately the future 4D positions of the UAV can be predicted and, how large *separation minima* consequently need to be to make sure that all uncertainties present are safely bounded in all possible situations.

In any case, airspace capacity will always have a certain limit and, thus, provisions need to be made *strategically* – i.e. at operations planning time, to avoid that the demand of UAS operations exceed the capacity of UTC to tactically handle UAS traffic. This drives the need for a traffic *planning service* (§4.9.1) that ensures balance between capacity and demand. Traffic planning can also handle separation at strategic level whenever separation is entirely provided based on 3D containment volume, i.e. solely on spatial separation.

The four cases envisioned, together with the discussion about the uncertainty associated with the prediction of the AV position need to be contrasted with the approach proposed by CORUS [2], in which a pre-defined airspace grid will be used to calculate the probability of interactions between subsequent flight plans, using this information to approve/reject new flight plans keeping the risk of interactions under acceptable levels.

As with flight data, all traffic-related information relevant to safety, security or privacy would need to be continuously recorded by U-Space traffic management services as evidence in case of the corresponding investigations, as well as to create a base of experimental data from which to learn how to improve operations.

3.10 Mission

It might be argued that the mission side of a UAS operation, in principle, corresponds entirely to the drone operator and that U-Space should not care about mission-specific details as long as the corresponding flight plan and its execution is made in compliance with all safety provisions and rules applicable. However, certain mission-specific aspects may entail important priority, security and privacy and other legal implications and, thus, U-Space needs indeed to be concerned about them as well[15].

Thus, in order to ensure that all drone operations are conducted in full compliance with applicable laws, U-Space needs to know the declared *purpose of the mission* so to check if it can be approved within the context requested, as well as have the means to confirm that the mission is conducted as planned or non-compliances are suspected, which may require intervention. U-space must have the opportunity to restrict areas of the airspace where a specific payload must not be used or specific missions cannot be conducted. For instance, a drone carrying in a payload considered dangerous

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[15] Some discrepancies may again be found in this regard, compared with the CORUS Concept of Operations for U-space [2], which considers that mission-specific aspects are out of the scope of U-Space.

(e.g. chemicals) may be denied to overfly certain areas or special provisions may need to be made in its case, such as keeping the traffic away or alerting emergency services or adopt different contingency/emergency procedures than usual. Another example could be a drone whose payload consists on an electro-optical sensor, which might have the ability to capture privacy-infringing imagery of areas where it should not. U-Space may still allow such drone to overfly a privacy-sensitive area as long as the drone switches off the sensors when flying over it. Off course, *audit trail* mechanisms need to be put in place to prove whether the mission has been conducted in compliance with the restrictions imposed. Yet another example could be that U-Space prioritizes airspace access or impacts operational efficiency (either positively or negatively) when required for deconfliction based on mission-specific aspects such as social or environmental interest. Another argument to consider mission-specific aspects as part of U-space is the pressure of regional and local governments to have a role in regulating low-altitude drone operations in their geographical areas, which implies the need to know mission-specific details to ensure the enforcement of specific regulations affecting drone operations set by regional or local administrations.

Therefore, *mission planning* capabilities need to interact with U-Space to share a number of relevant mission-specific details and to make sure that the mission plan conforms to the restrictions set up by U-Space. Subsequently, some sort of *mission conformance* capability needs to assist U-Space checking that the mission is being executed as planned and a *mission data recording* capability will serve as the abovementioned audit trail mechanism in case that a post-flight investigation results necessary (e.g. this could be used by the corresponding authority to check if the operator carried out drone applications he did not get clearance for).

One aspect to bear in mind is that the mission-specific data provided by the drone operator to U-Space at any point may itself be business-sensitive or just privacy-sensitive (e.g. identities of passengers or missions performed by police forces). U-space thus has to make the provisions necessary to maintain the required level of confidentiality of these data.

Another important aspect about mission-specific data shared with U-Space is its potential implication in determining liabilities and the level of insurance required to conduct certain missions.

As with flight and traffic data, all mission-related information relevant to safety, security or privacy would need to be continuously recorded by the drone operators as evidence in case of the corresponding investigations.

Table 10 below summarizes the relevant mission-specific information that needs to be shared in general with U-Space at mission planning time.

Mission plan data item	**Data representation**
Mission ID	Unique mission identifier (alphanumeric code)
Change number	Mission plan change number: 1 (first request), 2, 3, ...
Purpose	Catalogue code identifying the purpose (surveillance, inspection, taxi, experimental, etc.)
Geographic category	Domestic/international – including the list of incumbent countries
Operation category	EASA – open/specific/certified or similar simple classification
Safety category	Catalogue code classifying the level of safety risk (more comprehensive than EASA)
Security category	Catalogue code classifying the level of security (e.g. N/A, police, military, etc.)
Privacy category	Catalogue code classifying the level of privacy concerns of the mission

Mission plan data item	Data representation
Environmental category	Catalogue code classifying the level of environmental risk/impact of the mission
Confidentiality level	Level of confidentiality applicable to the mission data (plan and records)
Payload	Description of the PL used
Type	Code identifying the nature of the PL (special/dangerous cargo, sensors, passengers, etc.)
Cargo/passenger manifest	Description of the cargo or list of passenger identities when applicable
AV multiplicity	Single/multiple – if multiple, specification of type of multi-AV mission (formation flight, etc.)
Flights	{List of flight IDs of the flights encompassed by the mission}
Requesting operator ID	Unique ID of the operator requesting mission approval
Requestor's digital signature	Digital signature of the requested mission plan by the requesting operator
Approving authorities	{List of IDs of the official authorities (e.g. designated UTM SP) approving the mission plan}
Approvers' digital signatures	{Digital signatures of the approving authorities}
Status	Requested > pending > approved/rejected > withdrawn > completed

Table 10: Summary of relevant drone mission plan information shared with U-Space

3.11 Administrative

All the information needs discussed so far can be classified as operational, as they relate to the planning and execution of operations from the mission, flight and traffic stand points. Another category of information needs has to do with *administrative information*, not directly supporting the operations, but important to enable a lawful operational environment where all participants are held responsible and accountable for respecting the rules of the game. This category also includes off-operational services such as the UAV search and rescue.

Table 11 summarizes key administrative needs anticipated at a first glance.

Administrative info needs	Timeframe	Purpose
Law Enforcement	Execution & post-flight	Detection and punishment of violations according to the rules of the unmanned air
Reminders, warning and alerts	Planning, execution & post-flight	Individual notifications that require attention or immediate action by the receiver; UAV search & rescue
Risk Assessment and Insurance	Planning & execution	Calculation of related risks of a planned operations and information exchange with insurance companies
Special authorizations and exemptions	Planning & execution	Systematization of administrative processes to request special authorizations and exemptions

Table 11: Summary of relevant administrative information needs

In effect, the relevant U-Space authorities will need clear administrative processes and supporting instruments to enforce the regulatory framework. These processes should be as much as possible standardized and digitalized to facilitate the quick implementation of the administrative decisions and the distribution of relevant information to the affected actors. As a prerequisite, these processes will call for diverse U-Space information that has already been mentioned in the previous subsections. For instance, the mission-specific information shared by drone operators with U-Space poses the opportunity to identify the breach of laws, e.g. as related to privacy. *Administrative services* shall focus on the relevant information needs and mechanisms necessary to utilize this information from the point of view of the U-Space authorities.

In a first step, the administrative processes may need to access to specific flight and mission information to monitor the actual operations vs. the authorized mission/flight plans. This is based on the assumption that the flight plan authorizations will set up requirements in terms of capability levels, restrictions and other legal requirements which must be met by the UAS, for instance technical specifications, licenses, limited flight patterns or operational constraints, and that administrative processes will be initiated depending on the degree of non-compliance of a specific operation.

Connections to several U-Space information sources can be envisioned to perform this monitoring, for instance the *flight plan* that lists the connection between the UAS (with registered ID and characteristics) and the registered drone operator and remote pilot responsible for its operation, digitalized regulations, comparison of flight/mission records with authorized plans, insurance and many more. This will allow the *imposition of bans, sanctions or fines*, which will be personalized to the individual operators depending on their breaches. There is a need to identify those characteristics of a UAS operation that can never be infringed and those that are subject to changes without punishment.

At the same time, measures to communicate, control and enforce these obligations, which the operators are bound to, will need to be in place. Therefore, a vital system element from the perspective of the administration is the ability to direct *administrative reminders, warning* and *alerts* to participants in U-Space. As a primary function, these notices should be issued to timely convey administrative information in the different stages of the flight life cycle that are intended for an individual user of the system.

On the other hand, as flight plans will be automatically created, processed and granted, a need for a *personalized and automatized pre-flight risk analysis* (e.g. SORA [36]) is induced as part of the administrative instruments of the system. It is likely that in a future system this specific single-operation risk assessment is used by insurance companies to offer individual operation-based rates to the operators, as this is starting to evolve e.g. in UK right now [37]. Another interface with the administrative information services is the official exchange of historical records that documents the performance of the registered pilot or operator. At the same time, the relevant U-Space authorities may need to obtain information about the insurance status of an operator, e.g. for granting operating allowance and to forward liability cases.

We also need to take into consideration that, although flight plan authorizations will be automatically processed and granted in the envisioned U-Space system, some specific operations will still require specific approval processes or exemptions**.** These operations will be reviewed case by case and detailed ad-hoc risk analysis will probably be needed to assess each exemption.

Finally, the event of losing a UAV should be handled in an analogous way to how it is done in manned aviation, i.e. involving alerting and search and rescue services.

4 Concepts of drone information services

This section describes the set of *drone information service concepts* devised to satisfy the invariant information needs identified in prior §3.

The aim is to comprehensively cover all the information categories enumerated in §3 whilst keeping the discussion at high level, as the goal is to conceive and propose possible solutions that can help enlighten the much further discussion yet necessary around U-Space services. Thus, the focus here is to bring key preliminary ideas on how the proposed drone service concepts could potentially address 5 important questions, namely:

1) Which are the *challenges* concerning each service concept from the dual perspective of what problem does the service intend to solve and what other problems may it imply in doing so
2) What is the *output*, i.e. what information products does the service deliver
3) Which are the service *users/applications*
4) Which are the *inputs*, i.e. the sources of information that the service resorts to
5) How the *process* throughout which the service elaborates its information products looks like

Up to 35 drone services have been envisaged necessary to thoroughly support the generic drone operation lifecycle described in §2.2 – which further justifies why the scope in their treatment within the IMPETUS project has to be limited. Of course, the proposed list of service concepts is neither meant to be the only possible one nor even the best possible choice. The rationale behind the list proposed is based on the approach explained in §2, which combines the information collected by D2.1, the abstraction effort that brought about the generic drone operation lifecycle of §2.2 and the expertise of the ATM and UAS specialists within the IMPETUS consortium. Although commercial and technology considerations such as emerging IT technologies (e.g. cloud computing, internet of things, distributed ledger technologies, microservices, etc.) as applied to UAS businesses might possibly render a different view, we preferred to focus on the operational considerations and their implications in terms of safety and efficiency, leveraging to the extent possible the experience and lessons learnt within the ATM domain. The drone information service concepts presented hereafter are agnostic with regard to the particular choice of implementation technology.

An additional objective of IMPETUS is to explore how well the novel *microservices* paradigm and other emerging IT technologies may suit as such implementation technology choice. This will be covered in the upcoming deliverable D3.1.

4.1 Aeronautical

4.1.1 Airspace and drone zone structure

Airspace will play a significant role in the landscape which drones operate in, however the majority of the restrictions affecting drones will be outside the traditional recognized aviation structure. Therefore the term *airspace* will be used exclusively to refer to AIM (*Aeronautical Information Model*) defined volumes. Drone zones will be used as a generic term used for all volumes.

Any changes to the traditional airspace structure will have to be built around the current airspace model which is designed for manned aviation. With this in mind, we can expect to see new airspace sub-classifications established but we must ensure the new classifications do not adversely affect manned aviation and they should ideally enhance safe access to all airspace. An example are drones operations in an urban environment; operating a drone in an urban environment creates a number of unique challenges; how to track and monitor the operations, high traffic density, separation criteria could all be a problem. Hence, establishing an airspace classification based on the carriage of equipment analogous to the MEL (Minimum Equipment List) concept of manned aviation, '*minimum equipage areas'* or type of airframe, size, licensing, etc. may well address some of the issues whilst helping to structure access to airspace, encourage interoperability and improve safety.

Having a dynamic airspace where the rules of access could potentially change hour-by-hour or even minute-by-minute would provide a very flexible approach for drone operations, but it would make flight planning extremely difficult. In addition, Airspace Managers might change the 'access rules' at peak times of the day to either meet the demand for access the airspace or to improve their commercial return.

Although this dynamic airspace is unlikely to affect the hobbyist segment, the commercial operators might potentially struggle keeping track on what and where they are allowed to carry out drone operations. If the rulesets change on a regular basis, tracking which drone can do, what and when would be virtually impossible (depending on the frequency of change). To assist drone operators managing this complexity a *registration* system linked to a UTM server would be crucial. The registration system would contain detailed information about the UAS as described in §4.4 such as the type of drone, its performance capabilities, operational limitations, pilot licensing, etc., thus allowing flight plan approvals or rejection in a certain airspace to be automated.

With all the considerations above, a key question is whether the airspace will have both *static* and *dynamic* restrictions. To answer this question we need first to agree what is meant by *static airspace structure*. It could be argued that all airspace structure is dynamic; at some point it might, or will have to change. It's the period of time the change takes place what makes the difference; a few hours or a few years.

For instance, in the UK, airspace around airports has been the subject of special interest. Although most licensed airfields have an *Airfield Traffic Zone* (ATZ), providing an element of protection to manned flights landing and taking off, the airport might be keen to receive additional information on drones operations outside of their ATZ. To improve the airports' situational awareness about drone activity a number of additional drone zones with an associated ruleset could be established to mandate that all drone activity needs to be approved by the airport, or at the very least, request drone operators to engage with the airport and co-ordinate their activities. For ultimate flexibility, and to encourage drone operators to adhere to regulations, these additional zones would be need to be dynamic; changing depending on the runway in use, or the airports opening hours, etc.

Airports are not the only authority that might wish to establish '*Managed Drone Zones*'. As an example, in the UK a number of agencies have expressed an interest in knowing what is going on in the airspace potentially occupied by drones. For example, commercial companies are interested in drones operating above their assets and would ideally like to manage this activity. Whether the authorities would allow non-aviation industries to manage airspace and establish new 'zones' to protect their interest is a different question. Other authorities such as the police, port authorities, local councils, etc. have expressed an interest in managing airspace but how would this be managed and which agency would have ultimate control remains an open question. To manage and maintain all of the potential stakeholders, a centralized service is likely to be required. A service were a single source of truth can be maintained and any changes made to airspace, or a change to a rule set can be instantly promulgated to organizations who have been delegated the authority to provide a UTM service or manage a portion of airspace. The centralized authority must be interoperable with manned aviation through ANSPs or NAAs, to allow drone information to be shared with manned aviation thus ensuring safety.

Touching on the numbers of potentially interested parties, together with the possibility of dynamic drone zones, with a multitude of ever changing rules, we'd have to assess whether the current data formats are appropriate. Currently, the AIS (Aeronautical Information Service) data format is based around AIXM (Aeronautical Information Exchange Model). It's been discussed many times that this format is not suitable for drone operations, it can't produce the complex geofencing primitives (Figure 9) which will be required for the dynamic airspace. Whatever format is used to describe drone airspace, it must align to manned aviation which currently uses AIXM.

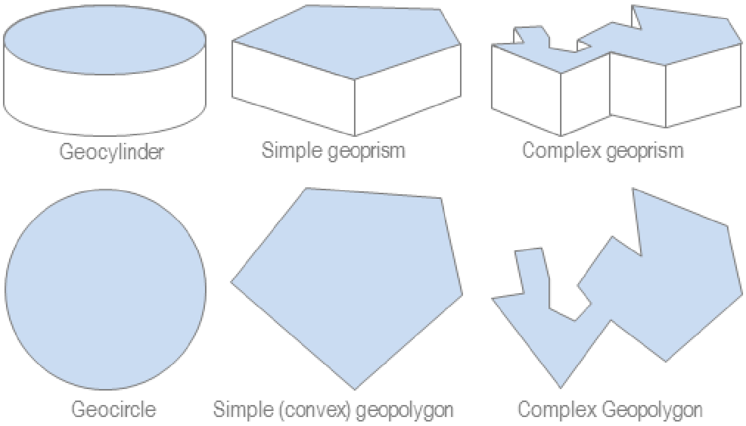

Figure 9: Representative geofencing primitives for the definition of airspace volumes

4.1.2 Drone port reference

Looking at the current model for manned aviation, each airfield with an ATC service manages its adjacent airspace to provide a service to arrival and departure traffic. When ATC is not available, it's good practice for pilots to carry out blind calls on a designated frequency, thus providing a basic situational awareness to other airspace users operating in the vicinity. Drone ports would be very different. Currently there is no indication to how many drone ports will be needed. In addition, there will be different ports for different types of drones; allowing for the size and weight for the drone, CTOL (Conventional Take Off and Landing) or VTOL (Vertical Take Off and Landing), will all play a part in determining their locations. For example, a small electric drone might be able to recharge its batteries by landing on the top of a lamppost, but a drone that carries people would need a much larger area, perhaps on top of a building. For larger ports sequencing (or rerouting) will potentially be needed as the numbers of drones could potentially struggle to self-separate leading to converging traffic patterns similar to those of manned airports. However in smaller ports, such as ones on the top of lampposts, drones could be expected to self-separate in order to reduce the drone port set up cost.

Elements of coordination between the drone port and the UTM are required to ensure the port was able to receive a drone, and that the drones arriving are deconflicted from the departing traffic. This coordination is unlikely to be addressed locally by the drone port and, thus, might need to be managed around a central managing capability, or at least there needs to be an act of negotiation between the port/recharging point and the UTM server. This is not to say that the drone port would receive the fait accompli, having to accept what the UTM system dictates. A communication link from the drone port to the UTM system would allow the drone port to inform the UTM system the order of arrival/departure, thus ensuring safety while any commercial agreements are met. In addition, the UTM system will need to know the position and 'state' of each drone and issue a clearance before a drone could be released ensuring the UTM maintains the single point of truth.

Not too dissimilar to that of manned aviation; before each flight begins execution the operator must identify as many diversion or recharging ports on the 'flight plan' as needed. As discussed in §3.3, a drone could be significantly affected by weather, resulting in the drone not being able to complete its operation and possibly having to divert. Due to the unpredictability of the weather, and not having the capability to predict ultra-localised weather patterns, diversion ports must be identified before the drone received a clearance.

The use of ad-hoc deployed ports might be adopted where the appropriate ground infrastructure is not in place to support certain drone operations. In a city or other urban environments, they are many potential charging ports so mobile ports are less likely to be needed. However, as drone operations carry out longer routes or transit through areas of predictable weather, deployable ports might be a reasonable option. Establishing rules around deployable ports will be challenging. There needs to be standardized procedures for identifying suitable launch/recovery sites; how close to residential areas, position with respect to ground hazards, access to different types of airspace and applicable rulesets, all will need to be considered.

Deployable ports will add complexity to the UTM service provider; the UTM system must be aware of the launch/recovery location, its availability timeframe, understand the types of drone making use of it and, consequently, provide the appropriate airspace access.

4.1.3 NOTAM

NOTAMs (Notices to Airmen) have been used for decades as a method of informing pilots of hazards/circumstances that could potentially affect their intended/ongoing flight. The number of drones being sold together with the numbers of registered users means that there are now more drones in use than manned aircraft. Today, most of the drone activity is VLOS operations, therefore the use of NOTAMS informing the operator of hazards, whether through a safety app or directly through AIS for the more aviation aware airspace users, is a sensible approach. However, with the rapid pace of evolution of drone capabilities, the introduction of new technologies and routine BVLOS operations, NOTAMs are unlikely to serve as an acceptable method of informing airspace users of drone activities.

As NOTAMs typically reflect exceptional situations, the manned aviation industry for a number of years has been advocating to reduce its reliance on and numbers of them. Currently there are many thousands of NOTAMs which pilots should review before flight, but this task is becoming increasingly difficult with the increasing numbers of NOTAMs being published. As the use of NOTAMs becomes prolific, a new safety hazard is created, i.e. important NOTAMS being missed. In addition, can the NOTAM system cope with the increase in NOTAM publications?

It's been suggested that a NOTAM relating to drone information is prefixed with the letter 'D'. In principle this sounds like a good idea, however we need to consider NOTAMs which apply to both manned and unmanned aviation. How should these be annotated? Regardless of whether the NOTAM system is adopted for drone flights, an automated system is required to monitor and scan messages and filter and highlight information affecting the flight of interest. We must ensure important messages are not missed.

Airspace restrictions and automated geo-fencing could be broadcasted through UTM, avoiding the reliance on using the NOTAM system. Alternatively, can a new system be established, e.g. a NOTDO's, (Notice to Drone Operators) for information of the sole interest to drone operators? Being able to automate the NOTAM system, having a sophisticated filtering system which only shows the NOTAMs and/or NOTDOs that affect an individual flight will be fundamental in ensuring important safety information isn't missed. Crucially, how this might affect manned aviation?

Having all airspace users, whether manned or unmanned aviation use the same notification system should ensure everyone is working from a single point of truth. However, the number of NOTAMS that need to be reviewed could quickly become a flight safety hazard on itself rather than the safety net it was designed to be.

4.2 Geospatial

Geospatial services are also critical as trusted sources of cartography information that may be critical to safety, either directly (e.g. terrain clearance) or indirectly (e.g. image-based navigation).

Future digital geographical information services in the context of U-Space shall be tailored to support UAS operations in a given geographical domain; as a minimum, such services shall provide terrain elevation and relevant cartography and/or satellite imagery; for specific UAS missions, the services might need to provide high resolution products and/or special features such as land use, vegetation, 3D representation of buildings, etc. The service might be feed with digital geographical information available from official agencies, with COTS cartography products and/or with information generated in the curse of routine or ad-hoc UAS operations. To ensure the liability of these safety critical datasets, a central validation and verification process will most likely need to be considered.

4.2.1 Terrain

A primary geospatial service is the provision of terrain data, which in its simplest form has to contain at least two coordinates set in the terrestrial coordinate system (latitude and longitude). Usually this pair of coordinates is complemented with a set of attributes, defining the characteristics of the point. For terrain, the measurement of elevation and surface type (water, stone, concrete etc.) are a reasonable minimum, but standardized formats (e.g. DEM [38]) contain up to 31 elements, comprising information such as the unit of measurement, source, date or resolution.

Field Name	Description
Coordinates	Pair(s) of latitude and longitude
Elevation	Height (above MSL) of the referenced coordinate (attribute)
Surface Type	Geological information about the surface (attribute)
Vegetation	Description about vegetation (e.g. grass, crops, trees, etc.)
Unit of measurement	e.g. meters, feet, inch etc.
Resolution	Resolution defined by the grid and/or sensing method
Formation date	Date characterizing information currentness

Table 12: Representative data provided by a digital terrain database service

Possible uses of terrain data are shown in but not limited to *terrain clearance*, *shortest path calculation*, *ground risk assessment*, *identification and assessment of emergency landing sites* or *localizing UAS emergency landing locations* [39].

The type of application and external factors are determining the required attributes and level of detail. As an example the following table shows the relevant data necessary to describe a simple 3D topology with additional specific attributes.

Geodata is accessible from multiple open source data portals in the internet. Examples are Natural Earth Data [40], Esri Open Data [41] and Open Topography [42]. Besides this, data that serves the high liability requirements for aeronautical purpose will most likely need input from official sources such as national cartographic agencies. The highest resolution found in the available material usually is 1:10 meters e.g. [40]. It is important to discriminate between *Digital Terrain Model* (DTM) and *Digital Surface Model* (DSM) which are both subcategories of *Digital Elevation Model* (DEM). As illustrated in Figure 10, *terrain models* only reference the ground surface whereas *surface models* include contours of vegetation, infrastructure and other surficial objects.

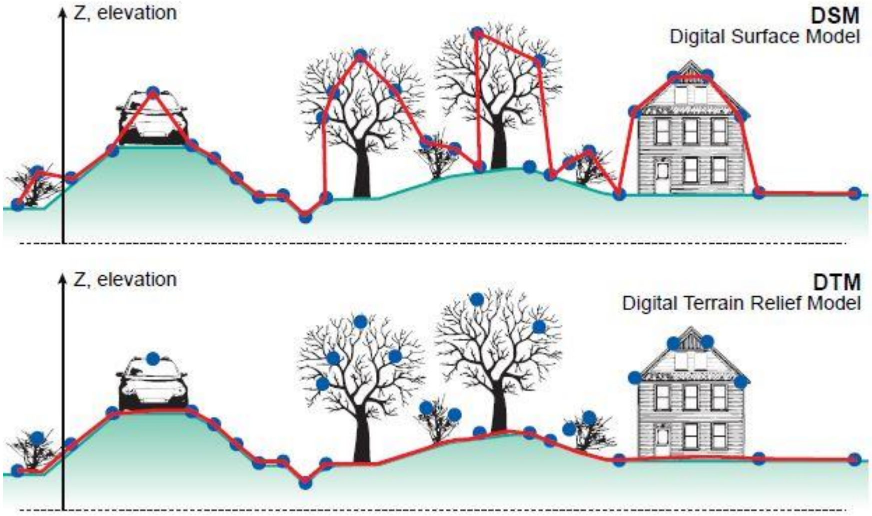

Figure 10: Difference DSM / DTM [43]

Since drones are often capturing geospatial data for mission or flight execution purposes, it seems to be an opportunity to use them as an additional input to enrich existing data sets with a higher level of detail. This form of crowd-sourced data contribution requires certain strategies to maintain the invariant need for high data quality (e.g. accuracy, completeness, currentness). For instance, this can partially be realized with a procedure called *verification by allocation*. In this method contributions are only added if a certain number of unique and independent sources are indicating similar values for a certain dataset, so that a predefined quality gate is passed [44][45].

With such services in place, terrain data can be provided to all participants in the U-Space context, including the operators, central authorities, service providers and many more. The level of detail that is available to a specific user might depend on his individual requirements as well as on the level of the service being purchased. Furthermore, it makes sense to have all data available as a constant streaming, but also it should be considered to have limited sector download to the actual drone, that serves as a backup in contingency situations which disconnect the drone from a steady data feed provided by the GCS or the operator.

Nevertheless, all datasets need to be accurate and current enough to serve the purpose of guaranteeing a safe and efficient conduct of operations. Possible solutions to this challenge are minimum quality standards defined by the central authority as well as a basic geo-service provided by officially authorized/certified vendors that is publicly available. Services that enrich this data might be considered as premium, to satisfy special demands resulting from certain types of operations or for the sake of specific mission-related purposes.

4.2.2 Obstacles to drone navigation

In contrast to terrain, the georeferenced storage of obstacles' position entails two additional challenges:

1) Their positions and appearance can be dynamic and
2) no public databases track them accurately.

From a data model perspective they could be treated in the same way as static terrain is handled: coordinates and descriptive attributes, for instance, coding the time of their occurrence, possible movement patterns, positioning uncertainty and likelihoods.

Consequently, a three dimensional, moving frame could be digitally constructed around them to make sure the obstacles are treated by drone navigation as impassable and taken into account just in the way it is done with topological terrain data. Obstacles which tend to be static – such as buildings, plants or snowdrifts, also need to be tracked and modelled differently than usual terrain data, since changes and deviations or much more likely. For instance a house could be expanded by scaffolding or satellite antennas. Therefore, it becomes clear that the geometric layout of obstacles needs to be charged with additional margins that reasonably take into account the uncertainty.

Field Name	Description
information provider ID	Unique identifier (alphanumeric code) of the data provider
Location	3D coordinates of the obstacle footprint
Height	Altitude AGL
Category	Type of obstacle (pole, crane, building, etc.)
Description	Relevant information about the obstacle {Obstacle 3D model if available}
Owner	For man-made obstacles, description of ownership
Timeframe	Period of time that the obstacle is known to be in place
Movement	Anticipated movements
Uncertainty	Uncertainties about obstacle data
Formation date	Date characterizing information currentness

Table 13: Representative obstacle-related data relevant to drone navigation

An example for a digital source is the FLARM® obstacle database [46] for general aviation purposes at the Alp region. They store about 44.000 objects, such as cables and antennas in Switzerland, Austria, Germany, Italy and France. Capturing further 3D structures as the buildings in an urban environment can be realized by the application of LiDAR sensors and other advanced photogrammetry techniques

[47]. Apart from that, NOTAMs could be interpreted as another source, although in the current practice their establishment only concerns obstacle relevant to traditional aviation. Furthermore, it is not desirable for both systems (unmanned and manned aviation) to increase the amount of traditional NOTAMs with far more numerous and frequent obstacles relevant to drones (compare §4.1.3).

As discussed in the previous section §4.2.1, integrated sensors of operated drones could be taken advantage of to generate a more detailed environment database, e.g. for urban scenarios (e.g. as proposed in [47]). The challenge here is the timeliness of the information. As moving or shape changing obstacles are not always possible to be verified by other contributors it would be conceivable to generate statistical distributions to determine the likelihood of occurrence based on the number of sightings and historical records. This data might not work as an authoritative forecast, which is needed for a legal flight path, but it could support risk analysis and data-based no-flight zones.

As indicated in §3.7 –surveillance information need 2), an additional, steady input of data could be elaborated from information provided online by drones currently operating which are equipped with the necessary sensors to detect obstacles in flight.

Analogue to the ideas presented for terrain information services, this will also result in a mixture of online and offline data that needs standardized procedures for validation and verification by a centralized authority. Deviation from official material would need to be thoroughly checked, keeping in mind that the claimed non-existence of a previously detected obstacle is more safety-critical than the false verification of its presence. The first scenario would lead to a false clearance with a possible collision, the second scenario to a waste of battery by flying an unnecessary obstacle avoidance manoeuvre.

4.2.3 Cartography

Nearly all UAS today use some sort of digital cartography in support to both operations planning and execution. The type of cartography information and the way it is accessed ranges from online servers of maps and satellite imagery to more sophisticated high resolution and/or specific products such as aerial/satellite ortho-imagery or thematic maps featuring special information layers such as land use, crops, infrastructures, etc. loaded ad-hoc into the GCS/RPS. Aspects such as sources, formats, availability, resolution, accuracy, currentness and other quality aspects of the cartographic information such as reliability or latency (when the cartography service is remotely accessed) are subject to a great heterogeneity.

Cartographic information may be used as the background layer in HMI (Human-Machine Interface) displays to serve as the visual baseline on top of which other information, whether mission, flight or traffic related, or aeronautical information can be overlapped. Frequently cartographic information is mission-specific and even mission-critical. However, as visual information, it may also become safety-critical in a couple of cases:

1) As it contributes to the situational awareness held by possible flight or traffic operators in the loop, and
2) As it is exploited to extract navigation information, as described in §4.6.3 using the so-called *image registration* technique.

Depending on the case, the criticality of the information may be subject to many different operational aspects such as real-time availability, continuity of service, the level of automation vs. operator involvement, the presence of safety nets or backup solutions, etc.

In the first case, the information might essentially consist on aeronautical charts, tailored to the scale and specificities of the operational context (e.g. urban environments). In the second case, the information would consist on ortho-imagery at the scale and resolution that fits to the flight altitude, speed and sensor characteristics of the UAV.

From a *capability-based* perspective, should any of these types of imagery information be assessed safety-critical in a particular context, it should be subject to standardization and certification and liability issues should be addressed.

In the second case (ortho-imagery for image registration) the ortho-images collected by the users of a hypothetical *ortho-imagery provision service* might be fed back to the service along with the camera pose parameters for the sake improving its quality. Another possibility is that they derive some sort of quality metrics by comparing the images provided by the service and the ones captures by the image registration sensor, and feed them back to the service.

4.3 Weather

As mentioned in §3.3, the spatial and temporal scales used in the global and regional numerical weather models available are too large to represent the local and micro-scale atmospheric effects needed to support drone operations. In fact, global and regional weather models capture fairly well geostrophic winds at high altitudes (outside the terrain boundary layer) and relatively low altitude winds over open and flat grassland, but not the wind field disturbed by higher vegetation, abrupt terrain and buildings. Previous research in the field of local and micro scale weather prediction in support to drone operations [48][49] has helped identifying four key issues:

1) Low accuracy within the terrain boundary layer, in general
2) Poor exploitation of local atmospheric observations
3) Deterministic approach – unable to yield a measure of the forecast uncertainty
4) Inability to determine the wind field near buildings, high vegetation or abrupt terrain

Prior R&D efforts have shown that issues 1), 2) and 3) can be addressed to a significant extent by, respectively, further reducing the spatial and temporal resolutions, the use of data assimilation solutions and the adoption of a probabilistic approach, without significantly deviating from the typical modelling approach to atmospheric physics of meso-scale (regional) models. In fact, the spatial resolution of meso-scale models can be increased to as much as in the order of 1-2 Km horizontal and about 25 m vertical to cope with local geographical domains representative of RLOS drone operations at relatively low altitudes. Further reducing the resolution does only increase computational cost but not accuracy. Thus, to address issue 4) micro-scale models with much higher resolution –in the order of meters, are needed, which require modelling the turbulent phenomena within the terrain boundary layer by means of a more realistic physical approach. This also leads to computational-expensive simulations, such as large-eddy simulation (LES), which, as of today, are unaffordable in real time for an entire city environment.

Figure 11 represents graphically the different nested geographical scales used in meteorological modelling, local and micro being the ones of interest to drone operations. In view of the discussion above, a unique weather service fulfilling the weather information requirements outlined in §3.3

seems very unlikely. This is the reason why we envisage two complementary baseline weather services: one for local scales, focused on issues 1), 2) and 3) and providing the initial and boundary conditions for the other one, nested, intended for micro scales and focused on issue 4).

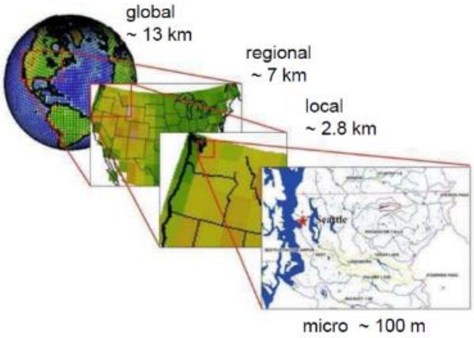

Figure 11: Different geographical scales in meteorological modeling [50]

In view of the discussion above, two different weather services are envisaged, each one intended for a different geographic and level of detail regarding the atmospheric data needed.

4.3.1 Local-scale weather

The concept of a *local-scale weather service* is intended to support forecast and nowcast of the atmospheric conditions indicated in Table 3 in local scales, based on online numerical weather prediction, focusing on addressing aforementioned issues 1), 2) and 3).

The service shall notify to subscribers the availability of new weather forecasts as they become available –periodically, in the nominal case, so they can download them for operational use (operations planning and execution). To that end, the service shall continuously maintain a nowcast of the atmospheric situation, which may also be provided to subscribers upon request. By comparing the nowcast with the last forecast in force, the service shall issue appropriate warnings and alerts to subscribers when deviations are found to exceed certain thresholds. Some users may also need past data for post-operational analysis, investigations or research purposes, for which the service is likely to be required to record all past weather forecasts provided during a period of time established by regulations (this implies provision for significant data storage capacity).

Envisaged users of local-scale weather information are mission, flight and traffic planning and execution capabilities, which need meteorological data for different purposes supporting both planning and execution of drone operations. The *micro-scale weather service* (§4.3.2) also needs local-scale weather information as a main input to elaborate its products.

Previous research [48] [49] has shown that this can be achieved by means of a meso-scale approach such as WRF (Weather Research and Forecasting model) [51], stretching down the spatial resolution to its limit (somewhere between 1-2 Km). WRF model is an open source meso-scale meteorological model[16] of complete physics capable of producing meteorological forecasts of a multitude of variables that define the atmospheric state. In particular, the ones reflected in Table 14, are

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[16] Some other relevant codes are HIRLAM (European), NAM (North American) or NHM (Japan)

envisaged necessary to derive the atmospheric conditions of Table 14 that support operational decision-making.

Symbol	Variable description
P	Pressure [Pa]
T	Temperature [K]
rH	Relative Humidity [%]
Td	Dew point [K]
u, v, w	Wind components [m/s]
TKE	Turbulent kinetic energy [m2/s2]
CR+NCR	Convective and non-convective rain [mm/s or time-accumulated]
Ir	Icing risk [%]
Cl	Cloudiness [fraction]

Table 14: Representative atmospheric variables

The spatial coverage of meso-scale models varies from a few to thousands of kilometres, and the temporal range varies from minutes to several days. The WRF model implements an Advanced Research Forecast (ARF) internal resolver that offers a great deal of flexibility in using different physics and boundary layer models, as well as significant parallel calculation efficiency. This makes it adequate to support probabilistic atmospheric forecast using the so-called *ensemble* technique, where several atmospheric scenarios associated to perturbed initial and boundary conditions and underlying physics parameters are propagated instead of just one, like it is the case in the deterministic approach. The evolution of the different scenarios (ensemble members) reflects the stability of the atmospheric forecast, thereby providing a measure of the associated uncertainty. In effect, in stable situations, all members evolve in a very similar fashion, maintaining the slight differences among them over time (*single attractor*). In some other situations the scenarios cluster up around two or more patterns (*multiple attractors*), indicating that there are several possible atmospheric evolution tendencies. In unstable situations, all members deviate significantly from each other, which means that any forecast will have a significant uncertainty associated. The probabilistic approach is intended to overcome issue 3) identified above.

To overcome issue 1) WRF includes several terrain atmospheric boundary layer (ABL) models to estimate the behaviour of the atmosphere at its lower levels. The ABL varies from a few meters to several kilometres depending on different latitudes and temperatures. The properties of the terrain, the vertical resolution of the grid (e.g. variable resolution, higher at lower altitudes) and the selected ABL model are key factors for modeling the lower layers of the atmosphere.

Finally, to overcome issue 2) WRF has the capacity to assimilate external observations that can be used as *truth* to increase the accuracy of the forecasts. These external data can come from different sources, such as forecasts from other numerical weather models and real-time observations from ground stations or aerial vehicles operating in the airspace of interest. This has considerable importance, as all drones operating in a net-enabled environment may potentially become providers of real-time atmospheric observations. In fact, this idea is already being exploited to its limit by some drone weather service providers, whose service concept completely relies on the cloud of real-time atmospheric observations feed by operating drones rather than on a physic model of the atmosphere as considered here.

Thus, the concept of local-scale weather service considered here resorts to essentially two complementary sources of information:

1) The global and meso-scale models periodically published by the official meteorological agencies every a few hours. Some of them are free (e.g. NOAA [52]), although deterministic and given without any compromise of quality or continuity of service. Some others are expensive (e.g. ECMWF [53]) but, in turn, offer some advantages, such as the probabilistic nature and certain quality of service guarantees.
2) Local observations of pressure, temperature and wind periodically made and downlinked by the cloud of drones operating in certain airspace (in support to data assimilation approaches) and, perhaps, extended atmospheric observations provided by a cloud of ground meteo stations. This involves airspace users publishing meteorological information, thus contributing to the weather service that, in turn, they are subscribers to.

4.3.2 Micro-scale weather

The concept of a *micro-scale weather service* is intended to support forecast and nowcast of average wind and the relevant statistical parameters representing adverse wind effects indicated in Table 3 (turbulence, gusts, thermals) in micro-scale geographical domains (see Figure 11), based on offline numerical weather prediction, focusing on addressing aforementioned issue 4). Such a service is envisaged to be a critical enabler for drone operations in urban environments, such as the emerging *drone package delivery* and *drone air taxi* concepts.

In effect, in urban scenarios, buildings and other artificial obstacles interact with the wind flow, giving rise to complex turbulent effects and the same occurs in non-urban environments of rugged relief. In these cases, the spatial and temporal resolutions required to correctly model boundary layers and viscous wakes are much finer (in the order of meters and seconds, respectively), which makes it necessary to resort to CFD techniques (Computational Fluid Dynamics) to derive and propagate wind currents in canyons, streets and urban areas to the extent that computation resources and processing times are acceptable for the specific application at hands.

One of such techniques that might potentially be used to implement the concept described is LES (large-eddy simulation). Figure 12 shows an example of a LES simulation of an urban scenario conducted by the Leibnitz Universität Hannover [54].

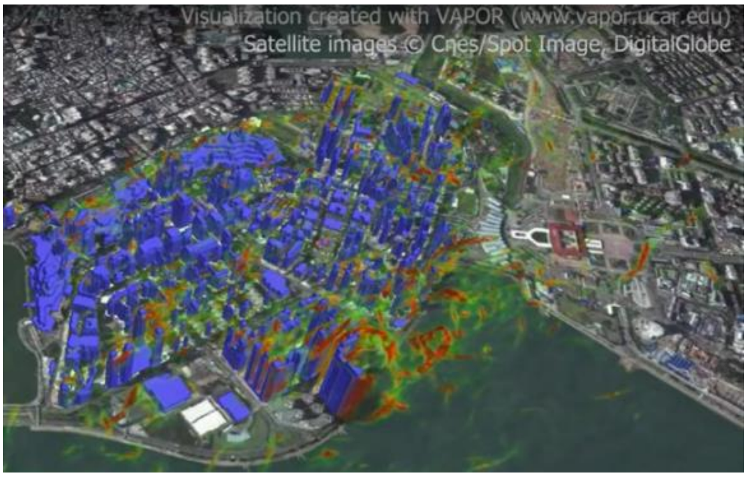

Figure 12: Sample Large Eddy Simulation of urban scenario

As of today, the geographical must be small and the limits, mainly the entrance of wind, must be known.

As of today, the use of these methods is limited to scientific projects and small micro-scale geographical domains. With the level of detail with which the geometry of an urban scenario can currently be known and the available calculation capacity, it is unlikely that the micro-scale weather service can be supported by online LES simulations (considerably expensive in terms of calculation demand).

Thus, one possibility could be to use LES techniques offline to characterize the influence of buildings or, in general, artificial or natural obstacles at micro-scale level as a function of varying wind conditions corresponding to larger scales (local-scale) with the idea to geographically confine the parts of the airspace where said influences are found dangerous for the operations of aerial vehicles. Other approaches being explored propose exploiting massive local observations coming from drones, meteorological stations and other emerging techniques (e.g. [55]) through artificial intelligence to learn about their deviations with regard to the local-scale forecasts, which are supposed to be characteristic of a given context. The idea is that, with sufficient training data for such context, the AI-derived algorithms would become able to predict such differences and, therefore, the micro-scale weather effects.

Several COTS micro-scale weather solutions have become available recently advertising ultra-high resolution and accuracy. While nowcast and even near-term forecast of weather aspects such as precipitation, icing, fog and storms at micro-scale level appears to have improved significantly in recent years, to the best of our knowledge no micro-scale weather forecast solution has been yet reported to safely guarantee avoidance of severe micro-scale effects.

4.4 System (UAS)

4.4.1 UAS characteristics

As pointed out in §3.4, a number of relevant technical and administrative characteristics of the complete UAS system needs to become accessible to U-Space actors others than the drone operator itself. The level of detail that is necessary to be shared will depend on numerous aspects such as the UAS typology, the *operation category* (open/specific/certified), the airspace and operational context in which the UAS operates, the modus operandi according to which it operates – including how both nominal and off-nominal (e.g. contingency) behaviour is managed, and the technology solutions that support the operation. An additional consideration that needs to be made when sharing technical and administrative data about a sophisticated system such as a UAS is the possibility to reveal IP (Intellectual Property) or business or security-sensitive information. As a general principle, only the information that is critical to guarantee the safety of the operations, support safety investigations or enable security, privacy and environmental control by law should be eligible to be shared. In addition, access to such information should be restricted by appropriate authentication and/or access control mechanisms to the users with a *'need to know'*.

Obvious details envisioned to be shared by a service providing the UAS characteristics of the drones operating in U-Space are:

- The aerial *vehicle ID*, to allow matching the unique identity of the UAV operating known by U-Space with the actual identity exhibited by the UAV by any possible means (plate, electronic conspicuity, black box, etc.) – see A.2 for a more detailed discussion on drone identification.
- The *vehicle model*, including manufacturer and model identifier
- The *vehicle type* in terms of its takeoff/launching and landing/recovery performances (CTOL/STOL/VTOL), possibly providing details of the launching/recovery system required in its case
- The vehicle's *maximum takeoff mass* (MTOM)
- The vehicle's *wake vortex category* (relevant for big UAVs)
- The vehicle's *weather susceptibility category*
- The *UAS airworthiness certificate* (relevant when operating under the *certified* category)

Such information might well constitute the heading data of a *standardized dataset* that needs to be defined as part of the UAS characteristics service.

If the UAS is expected to operate in isolation within a geofenced airspace volume, the AV trajectory – and thus the AV performances, may not be relevant to any U-Space actor other than the drone operator itself, as long as he guarantees the safety of the flight. However, if traffic interactions need to be considered, AV trajectories – and therefore AV performances, become a critical element concerning safety. In legacy UAS, the performance characteristics of the aerial vehicle are only known (typically, to a limited extent) within its proprietary GCS. No other system having a say on the AV flight trajectories, such as the traffic management services or a multi-UAV mission planning capability, has knowledge about AV performances and limitations (operational envelope), which is key for flight safety and mission efficiency.

Thus, including *AV performance characteristics* – e.g. in the form of a more or less sophisticated manufacturer-provided *Aircraft Performance Model* (APM)[17], as part of such standardized dataset

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[17] An APM provides key AV-specific information necessary to compute (predict) the trajectory of an AV, including its detailed 3D geometry, speed, timing, fuel/energy consumption, etc., which results critical to assess its safety and operational efficiency and, thus, to make sound decisions on how to operate it. To that end, the APM also provides the AV-specific parameters characterizing its operational limitations such as weight, speed and altitude envelopes, endurance, environmental envelope (e.g. service temperature range, meteorological conditions supported, maximum intensity of wind gusts and turbulence that the AV can withstand), etc.

would facilitate the access to key data needed to drive operational decisions (including through enabling trajectory prediction) in support to operations planning and execution from the mission, flight and traffic stand points.

Besides AV performance aspects, the UAS characteristics dataset will have to describe key features of the *communications* (§4.5), *navigation* (§4.6) and surveillance (§4.7) –i.e. CNS, solutions adopted by the UAS for both nominal and foreseeable off-nominal operating conditions.

Another important subset of information to be captured by the UAS characteristics dataset is the classification of its autopilot’s *flight guidance & control* and *flight management capabilities* (§4.8.2), including its *contingency management capabilities* (§4.8.4). With regard to flight guidance & control, it is important to characterize the method by means of which the autopilot accepts and executes trajectory definitions, since considerable trajectory interoperability issues are anticipated to appear as related to the large heterogeneity of legacy solutions. It is also important to characterize the susceptibility of the AV to Loss-of-Control (e.g. depending on actuators and flight control system quality and redundancies, wind conditions, etc.). Regarding flight management, it is important to characterize the method by means of which such a function may interact with the traffic management services – also anticipated to be subject to interoperability issues, as well as the possible ways in which the autopilot may manage the different in-flight contingencies (e.g. though a standardized library of contingency management primitives).

As explained in (§4.8.3) safely managing in-flight contingencies will require robustly planning UAS flights to avoid them to happen if possible and, in any case, prepare to effectively cope with them. This involves specific contingency planning and contingency management capabilities that the GCS needs to feature in addition to its nominal flight planning and flight management capabilities. Again, large heterogeneity and interoperability issues are expected here, due to the disparity of legacy solutions and operational contexts subject to different levels of criticality. To cope with this complexity, the UAS characteristics dataset will need to include data characterizing the UAS flight/contingency planning and management capabilities against a harmonized capability-based approach that still needs to be developed.

EASA NPA 2017-05 (B) [56] identifies further elements of key technical characteristics as relevant to Specific Operation Risk Assessment (SORA) and risk-based classification of drones, which are summarized in Table 15 below:

#	Technical characteristic	Description
1	Positioning limitations	Limitations in height/altitude and range of a vehicle in terms of positioning (accuracy) and technical capabilities
2	Flight control technology	Internal technology addressing the automated stabilisation of the airborne vehicle during the flight
3	Energy limitations	All technologic solutions that limit the kinetic energy transmitted by a drone during a potential collision. This can be realised e.g. by “soft/absorbing materials, special designs that facilitate the detachment of UA parts during a collision, blades protections, technologies that stop the rotors on impact, or any other technology that industry may develop in the future.
4	Collision Avoidance	Technologies that prohibit with mid-air or ground obstacles by automatically steering the drone away or provide sufficient warnings to the operating pilot
5	Automatic take-off and landing systems (ATOL)	Capability of a drone to take off or land on a dedicated spot without the need for piloting commands

#	Technical characteristic	Description
6	Loss-of-datalink management	Implemented procedures, that guarantee safe flight behaviour in case of a lost connection to the ground control station. Imposes different levels of capabilities for autonomous flights, return-to-home functions and remote sensing.
7	Electronic Identification	Technologies to remotely ask for identification data of the UAS and its operator

Table 15: EASA's technical characteristics of drones supporting risk-based classification

Element #7 of Table 15 relates to the AV ID described above. Element #1 relates to the *navigation capabilities* of the UAS (§4.6), including *contingency planning* (§4.8.3) *and management* (§4.8.4) *capabilities* for the case of LoG (Loss-of-GNSS). Element #4 relates to both *traffic surveillance capabilities* (§4.7) and *contingency planning* (§4.8.3) *and management* (§4.8.4) *capabilities* for the case of LoS (Loss-of-Separation). Elements #3 and #5 are relevant to contingency planning and management for the case of Loss-of-Engine/Energy (LoE) and element #6 relates to contingency planning and management for the case of Loss-of-Link (LoL). Finally, element #2 relates to contingency planning and management for the case of Loss-of-Control (LoC).

In some critical situations, contingency management may lead to the need to abruptly terminate the flight, possibly even scarifying the AV in order to prevent it causing a major safety accident. *Flight termination capabilities* such as independently or autonomously triggered *flight termination systems* or *energy limitation* solutions like parachutes or other shock-absorbing or disintegration solutions (Element #3 in Table 15) meeting certain performance standards might need to be mandated to allow certain drone operations and, thus, their specification would also need to be reflected in the UAS characteristic dataset.

In addition to the UAS capabilities related to the safety of the operations, other elements such as the payload carried out by the AVs may also have safety, security and privacy implications. That is the case of drones transporting people or toxic or dangerous payloads (e.g. pesticides) or any kind of sensor capturing information susceptible of privacy issues (e.g. cameras, communication systems, etc.). Thus, we envision that *AV payload characteristics* will need to be classified and, again, reflected in the UAS characteristic dataset.

Given the level of sophistication of the technologies realizing all the above mentioned UAS capabilities, it is envisaged that standardized maintenance programs need to be adopted, which would most likely include periodic technical inspections. Depending on the maintenance status of the UAS, operational limitations or even the complete inability to operate it might apply. Hence, the UAS characteristics service will also need to capture information about the maintenance status of the UAS, possibly electronically signed by the official technical inspection authority as it entails liability issues.

Finally, since the capability-based schema against which each UAS needs to be qualified may end up becoming significantly complex, it may be convenient to adopt simplifications that help both, systems and humans operators involved in UAS operations quickly understand and filter out key aspects of UAS capabilities. Hence, we suggest that a standardized alphanumeric code is assigned to each UAS encoding its capabilities in a way that is both human and machine readable.

4.4.2 Drone operators

A *drone operator* is an individual or an organization qualified to operate drones in U-Space, which is distinct from the individual that actually operates a drone, who is the remote *pilot-in-command* (PIC).

Although in simple cases a single UAS is operated by a PIC who may also be the accredited drone operator, likewise it occurs in manned aviation, a much larger casuistry can be found. In effect, a drone operator may operate a complete fleet of drones with the help of multiple PICs, as well as an individual PIC may be qualified to operate several different drones. As of today each drone is assumed to be operated by at least a PIC and this will probably hold in the near future. However, as higher levels of autonomy are reached in the future, it is likely that one single operator will 'supervise' instead of 'pilot' multiple drones operating almost autonomously.

To permit the operation of a drone in U-Space, it is paramount that both the drone operator responsible and the remote PIC in charge of conducting the operation i) are known to the system, ii) are adequately qualified with all the applicable licenses and other legal requirements in force, and iii) can be contacted at any time by the concerned U-Space services through well-established means.

To that end, the so-called *registration service* shall address the following information needs:

- Maintain two different databases, one for drone operators information and another for drone pilots information;
- Manage input and edition of the data stored in the databases, including security, integrity and authentication of the information;
- Control the access to the information to authorised users, based on a well-established access permission policy (according to specific 'needs-to-know').

The information handled by the registration service is also critical to ensure a clear scheme of responsibilities – and liabilities, for each and every instance of drone operation within U-Space.

Traditionally the need to avoid duplications and inconsistencies has made it necessary to resort to *centralized databases* managed by a unique actor (e.g. an authority or officially designated service). However, emerging IT solutions such as the so-called DLT (*Distributed Ledger Technologies*) [57] – popularized after the *bitcoin* [58], have significant potential to change that.

A possible *registry service* concept based on the centralized approach could look like the one reflected in Figure 13. The *U-space Authority* would be in charge of hosting, managing and maintaining the databases, including managing the access and edition permissions.

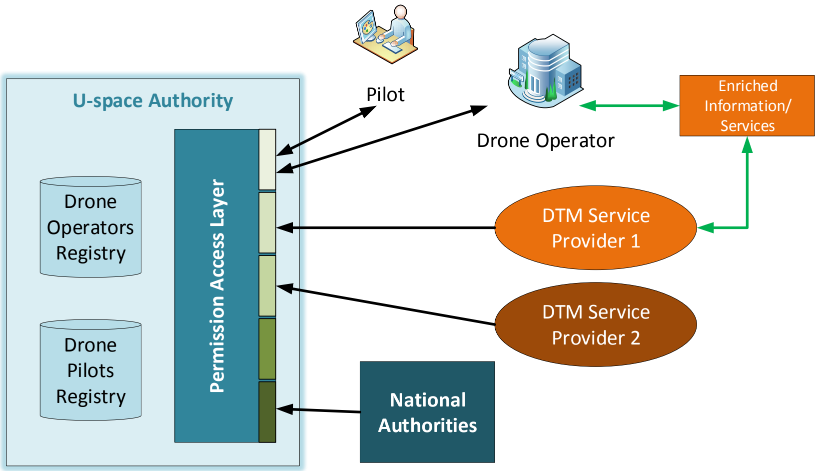

Figure 13: Centralised registration service and permission access to the databases

The information would be accessible to multiple *DTM (Drone Traffic Management) service providers* and other *National Authorities* or institutions (local authorities, police departments, etc). In particular, DTM service providers might consult this database to ensure that the drone operator requesting their services is properly registered and can operate in a specific airspace. For instance, by consulting this database, DTM Service Provider 1 might confirm that Drone Operator A has the proper operational approvals to operate in urban airspace of type 2.

DTM service providers might consult and enrich this information to help their customers design missions according to their authorized category of operations. This might allow DTM service providers to differentiate in an open market in which drone missions will become increasingly complex and sophisticated, so the drone operators are likely to demand supporting functionalities that facilitate the design of their missions.

Drone Operators and pilots need to be registered before any drone operation planning and ensuing execution activity is authorized within U-Space. To that end, the registry service might offer standardised functionalities to facilitate online applications for drone operator licenses and submission of pilot credentials. Currently, *Air Operator Certificate* (AOC) issuances in manned aviation depend on the country of registry and are stored locally by the National Aviation Authority's proprietary data centres. The adaption of AOCs to drones might require several changes, including the adaption of AOC information requirements to drone systems and missions, as well as enabling access to the information via a networked information sharing solution that, for affordability reasons, might likely be Internet rather than the dedicated telecommunications networks traditionally used in manned aviation.

Information about drone operator and pilots, including AOCs, licenses and contact data should be available online to all who petition it that have an acknowledged 'need-to-know'. This would include U-Space authorities, traffic management (planning and execution) services, official agencies designated to control safety, security and privacy or conduct related investigations, and drone search and rescue services.

Last but not least, the registry service should include essential information related to liability and insurance, such as the declared *type of activity* for which the drone operator license has been issued (e.g. leisure, aerial photography, inspection, surveillance, personal transport, taxi, law enforcement, emergency services, etc.) and the type and status of the insurance coverage.

4.5 Communications

We further discuss here how to approach a key subset of the communication needs identified in §3.5, namely needs 1), 2), 3), 4) and 5), which are the most critical ones with regard to flight and traffic management processes.

4.5.1 Traffic management link

In today's manned aviation Air/Ground (A/G) voice communication via standardized radio frequencies (VHF) and phraseology is still the most standard communication means that human operators – pilots-in-comand (PICs) and ATC controller officers (ATCOs), use to exchange operational information critical to safely and efficiently manage aerial operations. Significant efforts have been (and are still being) made worldwide to introduce datalink solutions that may replace voice communications (e.g. CPDLC – Controller-Pilot DataLink Communications) while enabling a diversity of additional digital Air Traffic Services (ATS) intended to enhance safety and improve capacity and efficiency (e.g. CPDCL [59], D-ATIS [60], D-VOLMET [61], ADS-B/C[29][62], TIS-B [32], FIS-B[63], ASAS[64], 4DTRAD[65], etc.). However, the adoption of such solutions is very limited and dissimilar across the world as of today, due to a number of reasons, including technology readiness, unclear business cases, heterogeneity of legacy fleet equipage, frequency congestion, etc., whose details exceed the scope of this discussion. A/G data communication between the cockpit and the Airline Operations Center (AOC) via ACARS [66] and SATCOM [67] has experienced higher adoption, though it is far from being commonplace.

As it relates to drone operations within U-Space the expectation is that most of the operational information concerning *traffic management* shall be communicated system-to-system-wise between the corresponding GCS and the automated U-Space *traffic management services* using a Ground/Ground (G/G) datalink that is most likely to be implemented over the Internet. This G/G datalink is still to be developed, but, it can be anticipated that many datalink services could be borrowed from the digital ATS concepts already developed for manned aviation and adapted – if not directly adopted, for UAS. Nevertheless some other datalink services may have to be developed ad-hoc to support the peculiarities of drone operations.

The G/G datalink connecting UTM services with all the GCS instances operating under their responsibility should retain the possibility to also convey human-to-human voice communications to enable U-Space operators directly contacting PICs to handle exceptional communication needs[18]. Such voice solution would be the norm, rather than the exception to enable PIC-ATCO communication if the UAS needs to operate in controlled airspace, at least in the short-term. In that case, it would be convenient that the UAV features a standard VHF communication equipment onboard as part of its MEL (Minimum Equipment List) and that the standard VHF voice communication between ATC and the PIC is relayed over the C2 link as indicated in RTCA DO-362 [68] to enable a redundant communication path for ATC-PIC voice communications.

In the longer term, as digital ATS services become commonplace in ATM –possibly supported by more than one standardized ATS datalink solution, drones operating in controlled airspace should also feature a standard data communication equipment onboard as part of its MEL, which again should be relayed over the C2 link to reach the GCS. Once again, it would be convenient that, conversely, the G/G datalink conveys the ATC-GCS data communications as a redundancy measure.

In U-Space environments where a networked communication infrastructure becomes available supporting both A/G and G/G communication needs, all safety-critical communications solutions related to flight and traffic management, namely CNPLC (A/G) and UTM-GCS (G/G) might be carried out based on such solution. Several telecommunications companies are exploring the possibility of leveraging existing 3G/4G and the upcoming 5G cell phone infrastructure to realize this concept [69][70].

#	Connection	Logical path	Voice	Data
1	GCS-UAV	A/G	N/A	CNPLC link
2	GCS-UTM	G/G	Internet (e.g. voice-over-IP)	Internet (e.g. VPN)
3	ATC-UAV	A/G	Standard VHF voice COM	Standard ATS datalink (e.g. UAT, VDL, etc.)

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[18] In principle, all communication needs between U-Space and the unmanned users operating in it are envisioned to be based on data

#	Connection	Logical path	Voice	Data
4	UAV-GCS	A/G	ATC voice relay over CNPLC link	ATS data relay over CNPLC link
5	ATC-GCS	G/G	Internet (e.g. voice-over-IP)	Internet (e.g. VPN)

Table 16: Summary of safety-critical communication needs

Table 16 summarizes all safety-critical communication needs mentioned above. For UAS entirely operating within U-Space, solutions #1 and #2 might result sufficient to enable all A/G and G/G communications needs. For those having to operate in controlled airspace, at the very least the voice part of solutions #3 and #4 would be required to enable ATCO-PIC voice communication without impacting existing ATC voice communication infrastructure. Solution #5 would be desirable for redundancy, although it means that existing ATC systems should be adapted to divert voice communications over the G/G link.

Many aspects of the communication solutions discussed are still needed to be investigated before any standardization decision can be mandated. Performance aspects in terms of availability, continuity, transaction time, transaction expiration time and integrity are paramount, although affordability and SWAP of related communication equipment are also key aspects. Last but not least, cyber-security is a critical aspect that needs to be addressed, given the fact that all the communication segments mentioned involve exposure to either wireless communication based on RF (e.g. A/G) or the Internet (G/G) – or both.

4.5.2 CNPLC link

While C2 (Command & Control) and mission communications are, respectively, safety-critical and mission-critical, in many legacy UAS solutions both are addressed through a single communications infrastructure with little or no redundancy at all. Many legacy communications solutions are proprietary and typically handle single UAV operations within RLOS range. In general, such solutions do not care about possible concurrent UAS operations, which might involve conflicts/collisions in terms of spectrum/frequency/radiation power that could lead to catastrophic events.

Regulations are expected to evolve towards separation between CNPLC (Command and Non-Payload Communications) – where standard solutions are likely to be mandated, and mission communications – where disparate/dissimilar solutions might be allowed, with a certain level of redundancy being required to the former. As more guidance on standardized CNPLC solutions becomes available [68], UAS pioneers are less expected to invest in developing/adopting proprietary CNPLC solutions. Moreover, BRLOS communications solutions will be increasingly needed, including supporting very long range and/or highly RF and obstacle-cluttered environments.

In contrast with *navigation* and *surveillance* equipment as related to UAS, about which not much regulatory guidance exists yet, the C2 link has reached a significantly higher level of maturity with the release of RTCA DO-362 [68] in September of 2016 exhaustively covering Phase-1 specification of Minimum Operational Performance Standards (MOPS) for UAS CNPLC link, and NATO STANAG-4586 [71] being the de-facto standard specification of the interface between the UAV (RPA) and the GCS (RPS).

Meanwhile the first DO-362-compliant CNPLC link prototype becomes a reality, most C2 link implementations available to date typically feature a one-to-one bidirectional UAV-GCS solution, the exchange of information, essentially consisting on the downlink of telemetry – including navigation information and UAV subsystems' health status, and the uplink of telecommands – including the ones intended to manage and control the flight trajectory, as well as all AV systems required for safe flight, plus those (nominally) issued by the PIC to manage contingencies and, ultimately, terminate the flight.

In view of the communication needs associated with the service concepts outlined in this section, many items of information related or critical to safety besides telemetry and telecommands shall also require to be exchanged over the C2 link, hence the increasing adoption of the term CNPLC[19].

As summarized in Table 17, in addition to the state-of-the-art in legacy UAS represented by telemetry and tele-commands[20], DO-362 already includes provision for the following transactions of information:

- Data from onboard navigational aids (downlink) and navaids setting (uplink) in support to standard IFR navigation based on terrestrial aids[21]
- ATC voice relay (uplink/downlink)
- ATS (Air Traffic Services) data relay supporting a number of services such as CPDLC, TIS-B, 4DTRAD, etc. (uplink/downlink).
- Traffic surveillance (intruders' data) collected onboard by the DAA (Detect and Avoid) sensors (downlink)[22]
- Airborne Weather Radar (AWR) data, if part of the UAV equipage (downlink)
- Video for remote PIC situational awareness enhancement during landing, taxi, takeoff and emergency procedures, if available (downlink)
- Security-related information (uplink/downlink), intended to protect the CNPLC link from deliberate unauthorized access and/or manipulation (e.g. hacking, spoofing, etc.), which, otherwise, might cause a loss-of-link (LoL) or, particularly worse, a Loss-of-Authority (LoA). To that end, *peer entity authentication*, *data origin authentication*, *data integrity*, *data confidentiality* and *access control* services have been specified.

CNPLC evolution	Downlink	Uplink
Legacy solutions	Telemetry: • AV state • AV operating modes and status	Telecommand: • Flight management commands • Flight control commands (not all UAS) • AV systems control commands • Flight termination command Other: • NAV augmentation info (not in DO-362)

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[19] For the sake of agnosticism across civil and /military domains, regulatory and standardization bodies, we will keep indistinctly referring to the three terms, CNPC link, C2 link (datalink) and C2 (data) communications to essentially represent the same concept

[20] With the apparent exception of the uplink of navigation augmentation information (e.g. Differential GNSS corrections and SBAS/GBAS integrity alerts))), not addressed by RTCA DO-362

[21] DO-362 follows NATO STANAG-4586 for flight management & control and navaids

[22] Consideration should be made of whether TIS-B might cope with the exchange between the UAV and the corresponding RPS of traffic surveillance information collected on each other side

CNPLC evolution	Downlink	Uplink
Additional guidance introduced by RTCA DO-362	• Data from onboard navigational aids	• Navaids setting
	• ATC voice	• PIC voice
	• ATS data (CPDLC, TIS-B)	• ATS data (CPDLC, TIS-B, 4DTRAD, etc.)
	• Onboard-collected traffic surveillance	
	• Airborne weather radar (AWR) data	
	• Situational awareness-enhancing video	
	• Security-related info	• Security-related info
Further needs identified by IMPETUS		• Ground-collected traffic surveillance (TIS-B)
		• Surveyed UAV position
		• Contingency planning info
	• Onboard atmospheric observations	• Predicted atmospheric conditions
	• Contingency management operational info	• Contingency management operational info
	• Warning: UAS operating autonomously	

Table 17: Information items exchanged over the A/G segment of the CNPLC link

Nevertheless, future CNPLC services should feature the exchange of even additional safety-critical information that, presently, DO-362 does not cope with. In effect, as advocated in §A.1, *autonomy* shall have a critical role in *contingency management*. Since contingency management will be performed in general by means of a collaboration between the humans-in-the-loop (PIC and possibly air traffic controller) and autonomous functions, a precise synchronization of related information has to be ensured so, to the extent possible, both autonomy and humans share the same situational awareness, have access to the same key information driving decision-making and stay informed of each other actions. The essential contingency management-related information that needs to be synchronized includes:

- Contingency planning information (uplink) coming out of the corresponding *contingency planning* functions that shall support *flight planning*, such as predicted communications, navigation and surveillance performances, trajectory segments or concerned geographical areas where navigation and/or communication issues are expected to occur, selected navigation and C2 link recovery points and manoeuvres, selected AV emergency landing or recovery locations and selected configuration of autonomous *contingency management* logic
- *Contingency management* operational information (downlink/uplink) such as contingency alerts, corresponding contingency management advisories generated by the autonomous functions onboard the UAV, PIC and/or autonomous responses (in particular signalling UAS operation in autonomous mode) and alert deactivation messages once the contingencies are cleared.
- Traffic surveillance collected on the ground (uplink) is assumed to be broadcasted (TIS-B) by ATS services using the ATS datalink, however, since such information is also fed to the RPS, uplinking it to the UAV also via CNPLC link would enable a redundant path, as well as a good replacement of TIS-B where such a service is not available (e.g. ad-hoc operations in airspaces where TIS-B service is not provided)
- UAV position derived from ground surveillance (uplink) in support to the onboard navigation function specially when in Loss-of-GPS (LoG).
- Downlink of onboard observations of atmospheric conditions to i) facilitate collection of actual atmospheric data, as explained in §4.3 (feeding as many local observations of atmospheric conditions as possible would facilitate achieving higher predictability of such conditions within the area where the UAV is operating, especially at low altitudes where the terrain boundary layer

adversely influences wind predictability), and ii) enable the RPS to know the deviation between observed and predicted atmospheric conditions, which may influence operational decisions.

- Uplink of predicted atmospheric conditions relevant to AV trajectory prediction is critical to enable coherence between air and ground trajectory prediction processes and, thus, to that of decision-making. Such uplink is to be made in terms of a dataset capturing pressure, temperature and wind forecasts for a particular 4D domain, periodically broadcasted by a digital meteorological service such as the one described in §4.3.1. Like in the case of TIS-B, uplinking such dataset also via CNPLC link would enable both redundancy and compatibility with an ad-hoc weather forecast solution whenever ATS (Air Traffic Services) or their equivalent in a certain U-Space context do not provide one.

Besides enabling the CNPLC link to handle the additional safety-related information described above, other essential considerations from the service stand point are *reliability* and *redundancy*. Reliability has to do with the maturity of the technologies chosen for the implementation of the CNPLC link (RF spectrum and modulation, antennas, HW, SW), while redundancy refers to diversification or duplication of elements such as physical path (e.g. direct RLOS vs. network terrestrial vs. satellite), RF bands and, again, antenna and HW/SW components. Design decisions regarding reliability and redundancy directly translate into CNPLC performance but, also, into SWAP and cost.

Future CNPLC solutions in the context of U-Space shall have to be scalable to fit platform-specific SWAP requirements, mission-specific range (RLOS vs. BRLOS), flight altitude and operational context (earth/water, remote locations, etc.) and safety requirements (e.g. level of redundancy required).

It is likely that no single CNPLC solution fits all needs and so that several ones, including legacy C2 solutions already adopted by existing UAS, networked CNPLC solutions based on existing/emerging terrestrial cellular (GSM/GPRS/3G/4G/5G) and/or satellite communications infrastructure, shall have to coexist.

4.5.3 Communications performance

DO-362 defines *Required Link Performance* (RLP) in terms of *availability*, *continuity*, *transaction time*, *transaction expiration time* and *integrity*, with varying requirements depending upon the operational context, as well as exhaustively discusses the numerous factors that affect such performance. DO-362 concludes that RLP is a trade-off between CNPLC link redundancy/diversity and automation[23] onboard the UAV, where the lower the later, the more stringent the performance requirements demanded to the CNPLC link.

Both predicting CNPLC link performance during flight planning and monitoring it during flight execution are two essential capabilities (i.e. services) needed to prevent and manage LoL contingencies.

Following the recommendation of DO-362, the first preventive measure that should be adopted to avoid LoL (given a specific CNPLC link solution) is to ensure that the RLP is met for the particular mission based on a *predictive assessment of the expected link performances*. First and foremost, a frequency management procedure has to be followed to avoid frequency collisions with other AVs or

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[23] DO-263 circumvents the use of the term ‘autonomy’ in spite of the fact that it is talking about the UAV ‘behaving automatically’ in LoL or near LoL situations

infrastructures using RF operating in the same area as the given UAS[24]. Next, a decision-support service based on computer models[25] that account for the *elevation and type of terrain* (§4.2.1), weather conditions (§4.3), frequency, spectrum, type of modulation, emission power, Tx/Rx antennae emplacement and characteristics (gains, radiation patterns, and sensitivity), etc, should help assessing expected CNPLC performance[26] for the particular UAV trajectory being planned or geographical operational area of interest. Flight planning assisted by such *predictive communications performance service* would produce a mission trajectory for which the given CNPLC link solution[27] is expected to meet the applicable RLP target or, at least, possible LoL are anticipated.

Another interesting application of such a predictive capability might be to support the selection of the ground antenna emplacement in a deployable RLOS link solution so the link performance is optimized over the trajectory or geographical area of interest. Considerable guidance about CNPLC performance prediction is already covered by DO-362.

During the execution of the flight, both ends of the CNPLC equipment are expected to work in synchrony, continuously monitoring CNPLC performance against the RLP levels set for the particular environment and operation and, whenever a shortfall is detected, raise the corresponding alert at both ends. DO-263 does not provide much guidance about how the CNPLC performance monitoring process shall be implemented or how LoL-related alerts shall be presented. Among the casuistry of LoL-related alerts, the most important ones envisaged are:

- Transaction expiration time exceeded
- CNPLC link unreliable (CNPLC integrity alert)
- Unauthenticated access attempt
- CNPLC link unavailable
- Loss-of-Link #X, if link #X in a multilink solution is lost
- Critical CNPLC equipment failure

These alerts can be sporadic events of short duration, intermittent, partial or complete. Onboard autonomy should assess the criticality of LoL-related alerts with reference to the LoL section of the *contingency plan* produced at operations planning time (§4.8.3) and determine if the repeated or sustained link performance degradation represents a safety risk, in which case LoL contingency alert shall be declared. The implications of a complete LoL are:

- Loss of telemetry, which entails loss of remote PIC situational awareness about the AV state, health condition and operating mode as reported by the AV, as well as of the AV environment (surrounding traffic and atmospheric conditions) as perceived by the AV's onboard sensors

- If the only source of surveillance information for the AV is its own telemetry, then the surveillance function (§4.7.1) becomes blind to that particular AV

- Loss of telecommand, i.e. loss of the ability to command and control de AV from the RPS

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[24] This procedure is assumed to be enabled by the U-Space service supporting *traffic planning* (§4.9.1)

[25] DO-263 provides guidance on the modeling and simulation tools used by RTCA to predict CNPLC link performance

[26] In terms of coverage, RLP aspects, possible frequency collisions with known RF emitters, etc.

[27] If the solution relies on multi-link or other types of diversity such as frequency diversity, that should be taken into account

- Loss of all kind of contingency management-related information generated onboard
- Loss of PIC's ability to intervene in any decision-making process related to how the AV is operated
- Consequently, whatever the AV does right after a complete LoL and meanwhile the LoL situation persists, including managing other contingencies, has to be decided and executed autonomously by the AV's itself. In other words, autonomy is inescapably required while the UAV operates in LoL condition.

Since communication performance plays a critical role in the safety of the operations, all the relevant performance-related events (e.g. issues detected, alerts raised, etc.) shall need to be recorded by the both the airborne and ground pieces of the *communications performance monitoring* function to support evidences in case of safety investigations.

4.6 Navigation

As discussed in §3.6, addressing Loss-of-GPS –or more generally, Loss-of-GNSS (LoG), will most likely entail the need to resort to additional sources of navigation information. We consider tree examples of possible navigation solutions that UAS might have to resort to in the near future, in order to address the GPS issue described; one based on conventional radio-navigation aids (§4.6.1) and two representative of potential non-conventional means, namely, navigation based on signals of opportunity (§4.6.2) and vision-based navigation (§4.6.3). Many other approaches are being investigated though, whose discussion exceeds the scope of this discussion.

4.6.1 Navigation aids

From the regulatory stand point, a natural argument to overcome the critical dependency of UAS navigation systems with GPS might simply consist on enabling them to navigate based on the conventional navigation solutions used by manned AVs when operating under IFR (Instrument Flight Rules). This essentially means standard radio-navigation equipment (when operating over continental areas) and navigation-grade inertial navigation systems or INS (when terrestrial radio-navigation is not available). However, as related to UAS, such an approach involves several problems:

- Certified standard radio-navigation and navigation-grade INS equipment is not currently available at the SWAP level that would suit relatively small drones. At that level, not even non-certified prototypes of such equipment are yet available.
- Even if standard navigation equipment acceptable as a *sole-means of navigation* becomes available for relatively small drones, navigation performance in terms of position, speed and attitude accuracies might not be sufficient from the standpoint of the PL/mission requirements, and, more critically, in some cases this might cause ground CNPLC antenna pointing issues leading to LoL.
- While no serious obstacles prevent radio-navigation to be scaled down in the short-term to much reduced SWAP, achieving so for navigation-grade INS represents a more difficult problem due to the adverse effects played by wind turbulence in strap-down inertial navigation at the scale of weights and speeds of small drones.
- The diversity of legacy navigation capabilities, qualities and methods, which range from direct guidance and fix designation to Precision Area Navigation (PRNAV), and instrument landing

systems of different performance levels entails a complexity which may be nonsense transferring to the UAS domain.

- The diversity of frequencies (VOR and ILS use VHF, while DME uses L-band UHF) and protocols of the RF signals that need to be acquired and processed onboard, which has considerable implications in onboard HW and antenna SWAP.
- The dynamic nature of UAS trajectories confronts the philosophy of standard radio-navigation procedures, where key safety aspects such as terrain and obstacle clearance and navigation performance are ensured at procedure design time.
- Conventional radio-navigation and INS are intended for 2D navigation, which means that altitude reference still needs to be based on baroaltimetry.

Thus, UAS navigation based on conventional navigation means does not seem to be a useful approach in general, except for the case of medium/large UAS that can feature the corresponding conventional navigation equipment plus are enabled to follow the standard [92] navigation procedures. This can be the case of UAS having to operate in manned IFR environments but not that of small drones within U-Space. Still, however, standard radio-navigation means might be resorted to by small drones fitted with the appropriate equipment to acquire and exploit their signals to perform GPS-denied recovery trajectories or as signals of opportunity as explained in next section.

4.6.2 Signals of opportunity

Modern signal processing techniques and resources and increasing RF (Radio Frequency) hardware integration scale are making possible the concept of exploiting widely available RF *signals-of-opportunity* (SOO) – in principle not intended for navigation, such as those supporting mobile phone communications[28], radio, TV, etc., to extract navigation information (e.g. [72]).

Some examples of sources of SOO that can potentially be used for SOO-based navigation:

- *Mobile phone network infrastructure* (GSM/3G/4G, and in a near future 5G), a very dense existing network of antennas continuously emitting according to well established signal protocols, with great terrestrial coverage, especially in populated areas. Upon subscription to a mobile phone company by means of a SIM (Subscriber Identity Module) card, data interactivity with the SOO sources is enabled, which might be used to improve the performance of SOO-based navigation in terms of accuracy (e.g. enabling ad-hoc positioning solutions) and integrity (e.g. through validation of data such as RF station geolocation, ad-hoc integrity data, etc.)
- *Satellite communications*. Several solutions are available, the most widely used when it comes down to portable devices being IRIDIUM (and its update, IRIDIUM Next, which will be completely implemented by the 2020s with improved bandwidth) [73]. With 66 satellites, IRIDIUM already provides global coverage with high availability.
- *Local beacons*. When a flexible ad-hoc solution is needed, beacon pods could be deployed at different locations to ensure coverage as needed. They can be configured to broadcast location information, emulate GNSS satellites (*pseudolites*) or mobile phone stations or repeat the signal

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[28] GSM, 3G, 4G and the upcoming 5G. 5G is of special interest as specific advanced techniques for precision positioning are built-in in its design.

of other navigation aids, provide a homing signal and act as an intermediate between drones, supporting V2V and/or V2I connectivity, in addition to supporting navigation.

The essential idea of exploiting SOO for navigation consists on deriving a number of observation equations that relate certain combinations of unknown and, perhaps, known aspects of the AV state (e.g. 2D/3D position, speed, attitude) with known, and, perhaps, unknown parameters of the SOO source and signal characteristics (e.g. emitter location, signal frequency, phase, data content, etc.) so the resulting mathematical system of known and unknown parameters gets determined or, preferably, overdetermined, thereby allowing information about the AV state to be extracted, if possible along with a corresponding measure of accuracy. Each observation equation formulates the equality of an observable variable as observed (measured) vs. modelled (expressed in terms of the known and unknown aspects of the AV state and SOO source and signal characteristics), possibly including an error term (e.g. bias, drift) typically unknown. Representative observables used include:

- Signal TOA (Time of Arrival) or TDOA (Time Difference of Arrival)
- Signal AOA (Angle of Arrival) or ADOA (Angle Difference of Arrival)
- Signal FDOA (Frequency Difference of Arrival), e.g. due to Doppler effect
- RSSI (Received Signal Strength Indication) or other signal-to-noise measure

These observables enable different positioning techniques such as interferometry, radio-goniometry, Doppler ranging, triangulation, etc. Depending on the kind of SOO signal, the measurement method may or may not require interaction with the emitter (*active* vs. *passive* methods), as well as involve more or less complexity[29], which ultimately translates into different levels of SWAP requirements (antennas, computing power) and performance (accuracy, reliability, outlier measurements, etc.). The observations may be simultaneous or sequential in time (with different synchrony and periodicity patterns), in which case the system of equations may adopt the form of a dynamic system[30], whereas the observation equations are nonlinear in most cases.

Depending on the amount of available observations that can be acquired and processed in real-time vs. that of the unknowns, the application of the techniques enumerated may bring more or less complete and accurate information about the AV state (in favourable scenarios a complete PVT solution can be achieved). In any case, such completeness and accuracy invariably depend on the number of SOO sources and their geometric configuration with respect to the AV (GDOP, Geometric Dilution of Precision) plus, perhaps, other aspects of the AV state (e.g., AV speed relative to the SOO sources).

Thus, the choice of SOO signals, observables and observation process or combination of processes has a crucial impact on the required SWAP and achievable navigation performance (in terms of accuracy, integrity, availability and continuity of service) or, in other words, on the compatibility of the solution with a given platform in a certain operation.

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[29] E.g. AOA may require directive or phase-array antennas, TOA may require a deep knowledge of the data protocol, FDOA might result difficult to measure for signals using spread-spectrum and/or quadrature amplitude modulation (QAM) techniques

[30] In principle, the fact that the AV is moving as SOO observations are collected could be taken as an advantage in order to improve observability.

The concept of an information service facilitating the exploitation of SOO for drone navigation consists on collecting as much information about the SOO sources as needed to derive useful navigation information from them and, thus, providing such information to the subscribed drones and drone operators. Representative examples of such information are included in Table 18.

SOO information aspect	Description
information provider ID	Unique identifier (alphanumeric code) of the data provider
SOO source ID	Unique identifier of the SOO source
Source placement	terrestrial/maritime/ aerial/space
Source motion	earth-fixed/(geo-) stationary/movable/moving
Source position	Parameters enabling the instantaneous computation of the 4D position of the SOO source (e.g. geodetic coordinates, orbital parameters, trajectory determination parameters, etc.)
Source position accuracy	Parameters characterizing the accuracy of SOO source position determination
Type of signal	COM (bidirectional)/TV/Radio/NAV signal/SUR signal/etc.
Signal specs	Parameter identifying signal specs (e.g. 3GPP LTE/LTE Advanced/etc.) out of a predefined list of known signal specs
Frequency	Primary operating frequency [MHz]
Other signal characteristics	Specific values of the variable parameters characterizing the signal – other than the primary operating frequency (e.g. channels, modulation parameters, emission power, miscellaneous accuracy measures, etc.)
Coverage	Parameters characterizing geospatial signal coverage
Data protocol	Parameter/s characterizing data decoding/encoding and interpretation (e.g. encryption method, data specs, formats, etc.)
Availability	Parameters characterizing availability of the signal (e.g. continuously emitting, intermittent, upon request/subscription, scheduled emissions/outages, etc.)
Integrity	Parameters characterizing signal & data integrity, i.e. to what extent the information about the SOO is reliable (e.g. SOO source position and associated accuracy broadcasted by the SOO source itself vs. estimated based on users' observations, integrity alerts, etc.)
Receiver/transceiver specs	Parameters identifying equipment (e.g. antenna, HW, SIM, etc.) specifications that the receiver/transceiver equipment must meet to synchronize with the SOO source.

Table 18: Representative information supporting SOO-based navigation

Depending on the source of SOO at hands, much of the information considered in Table 18 as required to extract navigation information may not be provided by the SOO or its provision may not be free-of-charge or it may not be available at all. For instance, many SOO sources such as GSM/3G/4G base stations do not broadcast their location nor there is any official database providing it. However, some initial web resources (e.g. [74], [75]) are appearing, starting to collect the location, type and even coverage of such SOO in particular. There are also different online resources that allow computing the satellite ephemeris needed to exploit space-based SOO sources.

In general, when the information of Table 18 with regard to a given source of SOO is not available, it has to be collected or built somehow. A possible data-driven approach is to exploit the redundancy of navigation equipment featured by the drones (and perhaps other users) operating in the area – e.g. when the GPS is working fine, to derive or validate the missing information (e.g. the position of a SOO source). The more such estimates are shared, the higher the confidence in the corresponding item of information becomes. Another possible approach (which could be used complementarily) is to deploy ad-hoc monitoring stations at known positions, which might also help assuring integrity.

A basic version of the service described here might consist on just supplying the minimum items of information about SOO sources needed to derive estimates of certain aspect of the AV state –either online or pre-flight, leaving up to the user to figure out how to assure the integrity of the overall navigation solution based on the level of navigation information redundancy available. As suggested, a more sophisticated approach might consider providing additional information that enables assessing the accuracy and integrity of the navigation information derived from the corresponding SOO. Yet a more sophisticated approach might, in addition, provide information useful to predict such performances and, thus, the availability of SOO-based navigation at planning time.

4.6.3 Vision-based navigation

A further non-conventional navigation source could be enabled through employing advances in EO (electro-optical) sensors and real-time image processing to extract navigation information from video streams captured by one or more such sensors already available[31] or purposely fitted within the UAV. The advantages in terms of navigation performance and independence[32] may well compensate the shortcomings associated with the additional SWAP and complexity[33] and the limitation of vision-based navigation to VMC (Visual Meteorological Conditions).

Several candidate vision-based navigation techniques being investigated in recent years are:

- *Optical Flow* encompasses a number of visual odometry techniques that allow obtaining an estimate of the AV absolute horizontal speed (*ground speed*) based upon relative movement with respect to stationary objects observed on the ground by standard monocular vision sensors
- *Semi-direct Visual Odometry* (SVO) relates to a more sophisticated set of visual odometry techniques, also suitable for monocular vision sensors that, besides estimating the complete velocity vector, also determines attitude information.
- *Image Registration* techniques could be synergistically applied to match images collected by a downward-pointing monocular EO sensor with a database of ortho-imagery stored onboard the UAV so 2D position and bearing (direction of the ground speed) can be derived.

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[31] E.g. synergistic use of the forward-pointing EO sensors intended for DAA

[32] EO sensors are interoceptive, i.e. do not depend on signals-on-the-space generated by external (ground or space based) auxiliary infrastructures, thus, offering immunity to jamming and spoofing

[33] EO mounting and/or corresponding image processing algorithms may require inputs from IMUs, calibration, additional wiring, dedicated processing HW, etc.

- *Line-of-horizon* detection is another vision-based navigation aid that might allow synergistically reusing a possible forward-pointing EO sensor supporting the DAA (Detect And Avoid) function to derive attitude information
- *Sun/Moon/star tracking*. Similarly to what has already been done in space for long time, the precise, known motion of the Sun, Moon and stars can be compared with observations acquired by an additional, specifically dedicated, monocular upward-pointing EO sensor to, again, derive vehicle position & attitude information. Nowadays, very low SWAP-demanding EO sensors[34] and image processing HW might help downscale the associated requirements so as to fit small UAS SWAP and affordability constraints.

With regard to image registration, it is anticipated that by just obtaining sporadic 2D position estimates, the containment of drift errors associated with inertial navigation (IMU) could be considerably improved, to the point that, in well-conditioned environments[35], a complete IMU-vision navigation solution achieving accuracies comparable to those of conventional IMU-GPS ones is envisioned achievable.

To support such an approach, a service such as the one described in §4.2.3 would result necessary, to provide the georeferenced ortho-imagery needed as the reference to compare collected images with.

But, in addition to just providing the reference ortho-imagery, another service should facilitate assessing if terrain characteristics and the current or foreseen atmospheric conditions – in particular, visibility, turbulence, flight altitude and speed, permit vision-based navigation techniques (not limited to image registration) and, if so, what is the expected level of performance.

Achieving so, would ideally involve interactions with the services defined in §4.2.1, §4.2.2, §4.2.3 and §4.3, as well as either the simulation of vision-based navigation performance with a high level of fidelity or, alternatively, the adoption of a data-driven approach that exploits the redundancy of navigation equipment to learn – and, thus, become able to predict, how such performance relates to its dependency variables (i.e. visibility, turbulence, flight altitude & speed and terrain characteristics).

4.6.4 Navigation performance

Legacy navigation fusion architectures (e.g. Extended Kalman Filters or analogous solutions) are typically tailored to specific navigation sources, which are assumed to be available at all times or, at most, contemplate a number of degraded configurations where one or more sources are unavailable. In view of the ever-increasing heterogeneity in the nature, availability and performances associated with the increased number of navigation sources that UAS are expected to rely upon, a much more flexible approach is needed to dynamically accommodate all the casuistic that can arise and still deliver the best possible performance in each case.

The modern navigation paradigm being advocated to fit this purpose is called *all-source assured navigation* [76]. The concept involves abstraction from the specific sensors so the key functions such

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[34] To detect and track the Sun, Moon and starts, a relatively simple and light EO sensor fixed to the AV mounted with wide field of view (FOV) optics is expected to render sufficient performance

[35] In vision-based navigation, performance depends on terrain evenness and richness of features that can be visually identified

as fusion of navigation information, integrity monitoring and alerting, fail detection and exclusion and provision of the best state estimate along with associated uncertainty can be implemented and work to a great extent, regardless of the specific sensors available at any given time. Such plug-and-play architecture should enable different observations relating different aspects of the AV state with different accuracies to be dynamically configured and exploited to render the best possible solution in terms of navigation accuracy and integrity.

When it comes to UAS, an important consideration that needs to be made is that no single means of navigation is likely to render the required navigation performance in all phases of flight, for all operational contexts, meteorological conditions and AV types[36]. Thus, a greater heterogeneity of navigation capabilities and performances is expected to arise as related to UAS, compared to what is usual in today's manned aviation contexts. As of today, IFR navigation procedures and airways over continental areas are designed based on available terrestrial radio-navigation aids, while oceanic routes require AVs to be equipped with navigation-grade INS. Thus, navigation availability is accounted for at procedure design time while acceptable navigation accuracy, integrity and continuity of service are expected to be achieved by the standard navigation equipment and infrastructures. Except when operating under standard IFR, UAS trajectories require a lot more freedom in the way they are designed and modified. In effect, UAS trajectories respond to mission requirements rather than standard air navigation procedural constraints and they may need to be planned ad-hoc with very short time in advance to their actual execution, re-planned while-on-the-fly or even dynamically generated without a prior plan.

Enabling a service capable to assess and predict expected navigation performance of heterogeneous navigation solutions is hence of the utmost importance. This capability shall have to account for the specific navigation equipment featured by a given UAS, as well as for the infrastructures that such equipment relies upon, to predict *availability* of navigation sources and the expected *accuracy*[37] and *availability of integrity*[38] corresponding to the different configurations of the navigation solution associated with all the possible casuistry.

Assessing or predicting navigation performance is far from being a trivial task. Let's consider integrity, i.e. the probability that navigation accuracy remains within acceptable limits. For standard IFR operations based upon conventional navigation means, navigation integrity is built-in by design as part of the navigation equipment and infrastructures (e.g. VOR, DME, ILS, INS), acceptable limits varying upon the applicable phase of the flight and type of IFR procedure. Thus, for instance, conventional radio-navaids are continuously self-monitored and have means to immediately report integrity alerts, while INS requires redundancy or even triple redundancy to ensure –among other performance aspects, availability of integrity. On the contrary, non-conventional navigation means, as well as those not certified as *sole means of navigation*, including GPS, do not feature acceptable

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[36] SWAP, affordability and availability of navigation information sources being the principal causes of it

[37] In general, navigation accuracy may depend on geographic position, which is characterized by the GDOP (Geometric Dilution of Precision), as well as, possibly on AV speed. E.g. in RNAV or SOO, 2D position accuracy shall depend on the number and distribution of available radio-navigation aids or, respectively SOO sources within range, while in vision-based navigation, 2D position accuracy shall depend on terrain elevation, feature richness and flight altitude. Vision-based navigation is expected not to work over broad water areas or in low visibility.

[38] I.e. how much redundancy of navigation information is expected to be available to perform navigation integrity monitoring

integrity mechanisms if at all. For this reason, GPS equipment certified as *supplementary means of navigation*[39] is required to implement receiver autonomous integrity monitoring (RAIM) functionality that exploits available redundancy of navigation information (e.g. when more than 4 satellites are in view or other sources of navigation, such as INS o other GNSS are available) to ensure navigation integrity.

Such *navigation performance monitoring and prediction* capability shall be needed during operations, as well as at operations planning time, or when re-planning or dynamic (mission-driven) trajectory generation are required, to assess if a given AV trajectory is either expected to be robustly supported by acceptable navigation performance or navigation vulnerabilities are identified.

A solid performance-based framework will need to be developed in order to articulate a coherent capability-based schema as related to navigation. In this regard, there is much work already done in manned aviation that should be leveraged or, at least, ensure alignment with. ICAO Doc-9613 – *Performance-based Navigation (PBN) Manual* [77] constitutes a principal reference. The PBN manual defines navigation performance in terms of *accuracy*, *integrity*, *availability* and *continuity of service*. Predicting all the four performance aspects of navigation is essential from the operations planning stand point, while monitoring accuracy and integrity and issuing the corresponding *navigation performance alerts* specifically concerns operations execution.

Among the casuistry of LoG-related alerts, the most important ones envisaged are:

- Navigation ascertained inaccurate
- Unavailability of navigation integrity
- Critical navigation equipment failure

While the specific figures and performance classification schema recommended by ICAO may have to be adapted to the non-conventional navigation means expectedly supporting UAS, the rationale, principles and guidance provided by the PBN manual are largely applicable to the development of a similar approach for U-Space. Other relevant references include [78] and [79].

Finally, as with communications performance (§4.5.3), due to the safety-critical character of navigation, all the relevant performance-related events (e.g. issues detected, alerts raised, etc.) shall need to be recorded by the both the airborne and ground pieces of the *navigation performance monitoring* function to support evidences in case of safety investigations.

4.7 Surveillance

Of the three categories of surveillance discussed in §3.7, *traffic surveillance* is considered the most critical one from the safety stand point. In effect, *terrain and obstacle surveillance* and *weather surveillance* both in principle admit planning-time solutions based on data in addition to execution-time solutions based on specific onboard equipment (not yet mature). Moreover, terrain/obstacles and weather surveillance do not directly concern any other AV operating in the vicinity. For this reasons we further address here surveillance needs as related to UAS focusing the discussion on traffic surveillance.

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[39] TSO-C129 and RTCA doc [68]

4.7.1 Traffic surveillance

Like with the navigation capabilities (§4.6), non-conventional traffic surveillance means shall have to be resorted to in order to guarantee acceptable surveillance performance as related to the surveillance needs identified in §3.7. One key challenge is that what is to be considered 'acceptable surveillance performance' involving UAS is largely still to be defined.

Concerning U-Space, a simple answer to the airborne traffic surveillance needs 5) and 6) identified in §3.7 might be that all AVs – whether manned or unmanned, that need to operate in U-Space are mandated to feature a two-ways electronic conspicuity means such as ADS-B in/out, SSR transponder or FLARM [80] to cooperatively exchange the relevant traffic surveillance data. However such an approach would be intrusive with manned aviation, cost being an important implication.

In particular airborne traffic surveillance need 6) is critical for the *Detect* piece of the *Detect and Avoid* (DAA) capability that drones operating in certain traffic environments shall be mandated to feature (see §A.3 for some important considerations about DAA). In that regard, the most reasonable architecture being advocated in the course of main known DAA R&D initiatives consists on combining both cooperative and non-cooperative airborne traffic surveillance sensors, whose outputs enter a sort of sensor fusion algorithm that ultimately, reports the potential *intruders*[40] being detected along with their estimated tracks[41].

In principle, a key aspect of acceptability for such an airborne traffic surveillance approach is that it matches human performance as far as detecting uncooperative intruders when in VMC (Visual Meteorological Conditions), as well as TCAS performance as it concerns cooperative intruders when in IMC (Instrumental Meteorological Conditions). However, given, the heterogeneity in AV sizes and performances associated with UAS, a fundamental question is whether or not human vision and TCAS performances will still result acceptable when the traffic encounter scenarios involve UAVs significantly smaller than typical general aviation AVs. Ongoing research [81] evidences that the answer to this question is negative. Therefore, key subjects of research are to assess i) which airborne traffic surveillance performance is needed to address the encounter scenarios considered reasonable, and ii) which combination of sensors and sensor fusion approach can render such performance in a way that results acceptable by regulators, yet is compatible with the stringent SWAP requirements applicable.

We envision that a combination of synthetic vision as independent airborne traffic surveillance sensor and low-SWAP ADS-B, SSR or TIS-B as the cooperative ones might possibly do the job.

Another key requirement for the *Detect* function is the need to provide a measure of the uncertainty associated with the intruders' estimated positions and speeds. In effect, characterizing such uncertainty is essential for the ensuing *Avoid* function to carry out its job in a robust way (i.e. with minimum false and missed alert rates and effective avoidance manoeuvres).

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[40] An intruder is a surrounding traffic that, due to its relative position and intent – whether known or inferred, is predicted to enter the ownship separation protection volume

[41] In state-of-the-art approaches to DAA, future positions of the surrounding traffic are extrapolated from current and past estimates of position and speed, with no attention paid to any knowledge of their intent. Including explicit intent information cooperatively shared by the AVs is expected to render significant advantages.

As for the ground surveillance need 7) –concerning how UTC would acquire both manned and unmanned traffic, several approaches have been proposed. Cooperative ones include:

- The deployment of ground or satellite [82][83] infrastructures to acquire the traffic surveillance signals emitted by all AVs equipped with electronic conspicuity means (ADS-B in/out, SSR transponder or FLARM)
- All GCS instances feeding ownship telemetry-derived surveillance data to the ground surveillance service
- 'Reverse TIS-B', i.e. likewise the prior solution, but including the traffic surveyed by the airborne traffic surveillance capabilities in addition to the surveillance data corresponding to the ownship
- Mulilateration based on a networked CNPLC solution such as 3G/4G/G cell phone infrastructures [69][70]

Non cooperative ground traffic surveillance means proposed so far include:

- Primary Surveillance Radar (PSR) adapted to detect small UAVs (e.g. birds/meteorological radars) [84] and 3D radar technologies –some emerging as anti-drone solutions
- More recently, advances in digital signal processing techniques have made possible the so-called *passive radar* solutions [85], which consist on exploiting sources of RF signals already existing - *illuminators of opportunity* (IoO) such as DTT (Digital Terrestrial TV), or deployed ad-hoc to detect and locate targets (AVs) through their RF signature by comparing direct and reflected signals (i.e. how the AVs perturb/reflect such RF signals).

All the suggested solutions have pros and cons in terms of cost, fleet equipage, availability, accuracy, SWAP, etc. Most probably a combination of them, i.e. a sort of '*all-source assured surveillance*' analogous to the *all-source assured navigation* concept explained in §4.6.4, might have to be adopted to attain 'acceptable' surveillance performance.

Regarding the traffic surveillance need 8) identified in §3.7, again, a simple answer might consist on that all UAS that need to operate in ATC environments are fitted with a certified SSR transponder. This is in fact the recommendation made by RTCA in DAA MOPS Phase 1 [86]. However this solution does not address non-ATC, non-UTC airspaces where both manned and manned AVs will ultimately have to coexist. In addition, SSR technology can handle a limited number of users. One possibility to approach this case is to extend to these airspaces the same airborne surveillance solution to traffic surveillance need 5) adopted for U-Space.

4.7.2 Surveillance performance

Likewise in the case of navigation performance (§4.6.4), an analogous *all-source assured surveillance* approach is envisaged to be needed as to cope with the increasing heterogeneity in the nature, availability and performances associated with the increased number of surveillance information sources expected to support UAS access to airspace. Such a concept would abstract key functions like the fusion of surveillance information, integrity monitoring and alerting from the specific surveillance sensors available at each moment, thereby dynamically adapting to all the casuistry that can arise in order to deliver the best possible surveillance performance in all cases.

Again, no single traffic surveillance means is likely to render the performance required in all cases and, therefore, much greater heterogeneity of traffic surveillance capabilities and performances is expected to arise as related to UAS, compared to what is usual in today's manned aviation contexts.

Enabling a service capable to assess and predict expected surveillance performance of the highly heterogeneous traffic surveillance solutions available in each particular context is hence of the utmost importance. This capability shall have to account for the specific traffic surveillance equipment featured by all UAS – and manned AVs in its case, as well as for the infrastructures that such equipment relies upon, to predict availability of traffic surveillance sources and the expected *accuracy* and availability of *integrity*[42] corresponding to the different configurations of the traffic surveillance solution associated with all the possible casuistry.

Again, assessing or predicting surveillance performance is far from being a trivial task. Such *surveillance performance monitoring and prediction* capability shall be needed during operations, as well as at operations planning time, or when re-planning or dynamic trajectory generation are required, to assess if a given AV trajectory is either expected to be robustly supported by acceptable traffic surveillance performance or vulnerabilities are identified. It is envisaged that this capability shall split in two components; one assisting flight planning and the individual DAA capability of each UAV from the stand point of airborne traffic surveillance requirements and the other assisting UTM from the stand point of ground traffic surveillance requirements.

Whether the consumer of traffic surveillance information is UTC, or the GCS or the *Assess* and *Avoid* pieces of the DAA equipment of a UAS, a solid performance-based framework will need to be developed in order to articulate a coherent capability-based schema as related to traffic surveillance. In this regard, there is much work already done in manned aviation that should be leveraged or, at least, ensure alignment with. ICAO Doc-9869 – *Performance-based Communication and Surveillance (PBCS) Manual* [87] constitutes a principal reference. The PBCS manual defines traffic surveillance performance in terms of *delivery time* – or transit time, *accuracy*, *integrity*, *availability* and *continuity of service*. Predicting all the five performance aspects of traffic surveillance is important from the operations planning stand points, while monitoring delivery time, accuracy and integrity and issuing the corresponding *surveillance performance alerts* specifically concerns operations execution.

While the specific figures and performance classification schema recommended by ICAO may have to be adapted to the non-conventional surveillance means expectedly supporting UAS, the rationale, principles and guidance provided by the PBCS manual are largely applicable to the development of a similar approach for U-Space. Other relevant references include EUROCONTROL-SPEC-147 [88] and [89].

Among the casuistry of alerts related with traffic surveillance performance, the most important ones envisaged are:

- Surveillance ascertained inaccurate
- Unavailability of surveillance integrity
- Critical surveillance equipment failure

Finally, as with communications (§4.5.3) and navigation (§4.6.4) performance, due to the safety-critical character of surveillance, all the relevant performance-related events (e.g. issues detected, alerts raised, etc.) shall need to be recorded by the both the airborne and ground pieces of the *surveillance performance monitoring* function to support evidences in case of safety investigations.

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[42] I.e. how much redundancy of surveillance information is expected to be available to perform surveillance integrity monitoring

4.8 Flight

4.8.1 Flight planning

In legacy UAS solutions, waypoint-based flight planning formulates the UAV trajectory as a sequence of 2D waypoints picked up form a map, possibly plus altitude and airspeed information.

Other UAS missions rely heavily on the realization of specific flight patterns in order to fulfil very varying applications, like systematic surveillance or photogrammetry. A main concept for the realization of flight patterns is the notion of *leg*, which is widely used in commercial aviation for the specification of RNAV procedures. Defining different types of legs allows describing different complex flight patterns using only a short number of geometric primitives such as straight lines, arcs and splines (see Figure 14). Every leg is parameterized by the initial and destination waypoints plus, perhaps, a number of additional parameters (e.g. type of geometry, turn radii, etc.) that convey more detailed information about the continuous geometric curve that connects them.

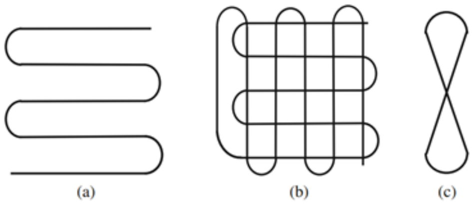

Figure 14: Sample drone flight patterns; basic scan (a), complex scan (b) and eight pattern (c)

These trajectory formulations (manually made by a human operator or automatically generated for specific mission trajectory patterns) is qualitatively assessed by the UAS pilot with no further model-based automatic assessment of the trajectory being typically made. The GCS usually performs flight planning without interacting with any UAS traffic planning or execution services, i.e. in isolation with regards to other UAS users' flight plans and traffic problems.

Section §A.4 of Appendix A provides an example of how planned UAS trajectories are described in nowadays using NATO STANAG-4586 [71] as a representative trajectory description format. Analogous trajectory description methods/formats such as ARINC-424 [90] and ARINC-702A [91] have been in place for decades in manned aviation to encode standard air navigation procedures and support flight planning. As pointed out in §A.4, flight plans made in terms of STANAG-4586 in general leave a significant amount of detail about the corresponding AV trajectory undefined, which negatively impacts its predictability, and similarly happens with the rest of legacy trajectory definition methods. It is important to highlight that, the larger the uncertainties about predicted 4D positions of AVs are, the bigger the volumes of airspace around them need to be cleared in order to guarantee safe separation. Thus, AV trajectory predictability is pivotal to the compromise between safety and airspace capacity.

Future flight planning services in the context of U-Space shall combine trajectory modeling primitives (e.g. NATO STANAG-4586 waypoint-like and, perhaps other emerging methods) with high-fidelity *trajectory prediction* (TP) capabilities that may need to account for AV performances (including operational limitations, from §4.4.1) and/or atmospheric conditions (wind, pressure and temperature, from §4.3.1) to provide the flight plan requestor (e.g. the mission planning service, §4.10.1) with i) guarantee of feasibility and ii) the predicted trajectory so the requestor can assess whether it fits the mission objectives or further tuning is needed. Flight planning will use aeronautical and geospatial information services (respectively from §4.1 and §4.2) to acquire all the corresponding information relevant to the flight plan being created, which will support feasibility assessment as well as developing companion contingency plans to the nominal flight plan (§4.8.3).

During planning-time the flight planning service shall interact with the traffic planning service (§4.9.1) service to schedule the mission trajectory in space and time and get approval for execution as scheduled. If trajectory re-planning is needed upon mission, flight or traffic execution events, the flight planning service shall interact with flight execution (§4.8.2), traffic execution (§4.9.3) and mission planning (§4.10.1) to accommodate the changes in the intended trajectory safely and, to the extent possible, with minimum impact to the mission.

As discussed, AV trajectory predictability is cornerstone to anticipate and optimize system performance from the three angles: mission (effectiveness, efficiency), flight (feasibility, safety) and traffic (airspace capacity, safety) and it all depends on the detail and quality of the information handled by the flight planning service.

The probabilistic approaches indicated in §3.8 are envisioned to help rendering a measure of trajectory prediction uncertainty, which might be exploited by the flight plan service to increase robustness of the flight plan.

Regarding separation from terrain and obstacles, in manned aviation, appropriate clearance margins for airspace routes and standard departure and arrival procedures are guaranteed once and for all at airspace/route/procedure design[43] time (i.e. way before operations planning) with the consequent limitation that AV operations must necessarily be constrained to such airspace structure, routes and procedures. In the case of the UAS, because of the ad-hoc and more dynamic nature of their mission trajectories, terrain and obstacle clearance may have in general to be determined at operations planning time or even at execution time, which most RPS do, though following non-standardized proprietary approaches[44].

4.8.2 Flight management

In legacy UAS solutions, flight execution is performed jointly by the GCS and the onboard autopilot. Flight execution involves some sort of *flight management* function in charge of setting up the reference AV trajectory to be flown (i.e. decide what trajectory to fly) and the flight guidance and control functions, in charge of executing (i.e. implementing) it.

The flight management function can be notionally performed manually by the PIC, by an automated system or, more typically, by a combination of both. Also, the automated system can be fully implemented within the GCS, fully onboard or have both ground and onboard components.

Legacy UAS flight management solutions tend to be overly simple. For instance, they usually do neither perform monitoring of flight conformance against the given flight plan nor offer sophisticated capabilities to safely and efficiently handle in-flight contingencies. For instance typical solutions for LoL and LoG contingencies consist on flying the UAV from the current position directly back to the base or to a designated recovery location, regardless whether such straight trajectory violates existing NFZs in the way or separation with surrounding traffic. For more severe contingencies such

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[43] As specified in ICAO Doc-8168 [92]

[44] Terrain and obstacle data not guaranteed accurate and/or current; separation minima proprietarily chosen

as *loss-of-Engine/Energy* (LoE) or *Loss-of-Control* (LoC), current solutions consist on an emergency flight termination (EFT) system, possibly combined with a parachute, which, depending on the implementation, might still be risky from the safety stand point plus heavily impact cost-efficiency. Besides these limitations, existing flight execution capabilities, for the most part, designed for single UAV operations, do not contemplate separation issues at any timeframe –i.e. no interaction with traffic management services or Detect and Avoid (DAA) capabilities.

Future UAS flight management services designed to operate in U-Space in general shall have to combine pieces of functionality allocated to both the ground and the air segments working in concert.

The ground piece shall support rigorous trajectory execution from the ground segment as per the detailed flight plan produced by the flight planning function (§4.8.1). To that end, it shall be feed by the flight planning function with the flight plan for each UAV whose flight needs to be monitored and managed in execution-time. The ground flight management piece shall be in charge of up-linking the flight plan to the airborne counterpart and activating it for execution on each UAV that takes part in the mission; as mission execution proceeds, the ground flight management piece shall continuously analyse available telemetry flight data (aircraft state, avionics, CNS functions and engine health, etc.) to monitor flight conformance to plan, alerting of and recording flight non-conformities[45] if the case arises. The ground flight management component shall work in close loop with the corresponding ground mission execution capability (§4.10.2) to report flight execution progress relevant to the mission in nominal situation, as well as the activation of contingency plans as a result of contingency events. The ground flight management component might automatically generate contingency trajectories to safely manage flight contingencies and propose them to the PIC – who is likely to hold the decision-making authority whenever possible, for evaluation and amendment. Such flight execution authority might be overridden by the airborne flight management piece whenever autonomous decision-making is inescapably needed –e.g. when contingencies lead to do-or-die situations.

On the other hand, the onboard flight management piece shall support rigorous trajectory execution from the airborne segment as per the detailed flight plan feed by the corresponding ground counterpart. Feed with the onboard navigation data provided by the navigation function (§4.6), the onboard flight management component shall coordinate the flight guidance and control functions to ensure that the intended (reference) trajectory is followed within the applicable tolerances. The onboard flight management component shall feature capabilities to autonomously generate and execute contingency trajectories to safely manage flight contingencies whenever the severity of the situation requires it (e.g. due to LoL situation or very short reaction time available or no PIC response). In general, the onboard flight management piece might have to interact with the corresponding airborne mission execution capability (§4.10.2) to report flight execution progress relevant to mission in nominal situation as well as the activation of contingency plans as a result of a safety event. In particular, the onboard flight management component might have to feature advanced autonomous flight management capabilities such as autonomous generation of holding patterns, trajectories to a destination point avoiding NFZs or others such as mission-driven trajectories.

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[45] Flight non-conformities in this case may occur due to adverse wind conditions or performance degradation, which make the UAV no longer able to comply with the required trajectory uncertainty boundaries

Both the ground and onboard components of flight management services shall have to work in synchrony to ensure that the behaviour of the UAV is always predictable under any circumstance, even when operating autonomously as a result of contingency situations.

If flight re-planning becomes necessary for any reason (e.g. mission, flight or traffic issues, including contingencies) the flight management services shall ensure the necessary coordination with all concerned actors (e.g. traffic services, surrounding AVs) so the new/amended flight plan is safely allocated within the system. Such trajectory allocation may follow a negotiated process if circumstances permit or be imperatively determined by either the traffic management services or by the flight management services for criticality reasons, but always following a well-established protocol.

4.8.3 Contingency planning

As part of the flight plan, which describes the nominal trajectory intended to be flown, drone operators shall likely be required to also produce a companion *contingency plan* that explicitly describes the level of susceptibility of the UAV chosen to foreseeable in-flight contingencies along with the predetermined way in which such contingencies would be managed by the drone, should it have to autonomously react to them.

Of the five categories of potentially safety-critical in-flight contingencies mentioned in §3.8 (LoS, LoG, LoL, LoE and LoC), LoL and LoS are the ones that the aviation community is presently most concerned about. In fact, after significant research efforts made over the course of last years, some initial guidance on the CNPLC (Control and Non-PayLoad Communications) link and DAA (Detect and Avoid) has recently become available after the publication by RTCA of the respective MOPS DO-362 [68] and DO-365 [86], partially addressing LoL and LoS issues. Little awareness exists yet about LoG, even though most small UAS navigation solutions critically rely on GPS. LoE still represents a different scale of safety concerns at least for small UAS, due to their lower MTOM and energy[46] plus the fact that fitting a parachute may be a reasonable option from the safety stand point. LoC is so far hardly mentioned in the UAS literature. In effect, although small UAS are more susceptible to LoC than larger ones or manned AVs, it is assumed that the associated safety risk is subject to the same considerations as LoE. However, when, for SWAP or efficiency reasons, the inclusion of a parachute – or equivalent energy limitation solution, is not affordable, LoE and LoC may represent a major safety concern as well.

In line with the comprehensive approach to contingency management advocated in §3.8, sections §4.5, §4.6 and §4.7 discuss CNS issues and how CNS infrastructures and services might evolve or be adapted to more robustly support UAS operations. In particular the need to enable decision-support tools (DSTs) capable of predicting CNS performances in support to contingency planning is argued.

Once a given UAS with given performances and CNS capabilities is chosen to operate in a given context, a *contingency planning* capability is firstly concerned with using such tools as part of the planning process to anticipate expected CNS performances as related to the specific flight trajectory being planned. For instance, the response to an expected LoL because of an anticipated defective radio coverage affecting certain trajectory leg may be different to the response of a totally

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[46] The sum of kinetic, potential and internal (e.g. chemical/electrical) energy, which is a key consideration to assess the risk associated with a potential crash

unexpected LoL because of unknown reasons, and so may happen with expected degradations of the navigation or surveillance performances.

Secondly, the contingency planning capability, knowing exactly how the *contingency management* logic (§4.8.4) handles contingencies, has to assess if the contingency management procedures applicable to each and every one of the contingencies potentially experienced at any point of the trajectory being designed would succeed to ensure safety. Otherwise the flight plan should be considered not contingency-proof, which means it should be amended or exemptions should be applied to approve it. This may consist on simulation-based what-if to ensure that, should any foreseeable contingency situation occur at any time during operation execution, the contingency management logic will safely cope with them. In that iterative process, contingency planning may have to choose among several contingency management alternatives available in order to help attaining a contingency-proof solution. This restricts how the contingency management logic will operate and, thus, the corresponding choices found to render a solution need to be recorded as part of the contingency plan elaborated. The idea is to make sure at planning time that all contingency management behaviour is predetermined and thus it results predictable to all concerned parties – including the ground segment of the UAS itself, in case that, for any reason, the contingency management procedure has to be triggered and implemented by the UAS operating autonomously.

Once the flight plan is found to be contingency-proof, all the data that parameterizes the contingency management logic, which was assessed successful to cope with the foreseeable contingencies shall be formally captured by the contingency plan.

The idea of contingency planning is, thus, to determine at planning time how contingency management will behave at execution time so to ensure that such behaviour is deterministic and, therefore, predictable. However, when considering UAS operating in controlled environments managed by human air traffic controllers this might not be enough. In effect, the fact that the contingency behaviour is deterministic and predictable does not preclude that such predictable behaviour is defined ad-hoc for a specific operation of a specific UAS –contingency management capabilities may vary widely across different UAS. This might introduce large diversity on how contingencies are managed, which may not be a problem for an automated traffic management system, but it certainly would for human operators. Thus, to facilitate human air traffic controllers understand how UAS will behave in case of contingency, such behaviour might need to be standardized to a large extent.

4.8.4 Contingency management

At operation execution time, a *contingency management* capability is required to assist the remote PIC in safely coping with the foreseeable in-flight contingencies and, ultimately, take over the PIC to handle contingencies autonomously, should the situation require it to guarantee safety. In general, each contingency management solution should include the following steps:

1) During nominal execution, routine monitoring and preparation tasks need to be performed with regard to each category of contingencies to identify the contingency situation in case it happens and ensure readiness to cope with it.

   Thus, the UAV shall monitor the performance of its critical systems, in particular, that of the CNPLC link, navigation function and engine/energy systems in search for potential contingencies (respectively, LoL, LoG and LoE). The UAV shall also monitor its flight control performance in search for ill-conditions such as actuator failures or severe wind (e.g. gusts, heavy turbulence) that may cause *Loss-of-Control* (LoC). Regarding LoS, even though separation assurance is part of the job of U-Space traffic management services (§4.9.1 & §4.9.3), separation infringements are likely to happen due to a number of reasons (e.g. high traffic density, degraded vehicle or navigation performance, third-party AVs deviating from their flight plans, etc.). Therefore, the UAV shall continuously monitor its separation with surrounding traffic, as part of its DAA capability, based on the traffic surveillance means available onboard.

2) As soon as the contingency has occurred, its criticality shall be immediately assessed and, consequently, a decision needs to be made (possibly autonomously) on whether to *continue execution as planned* (e.g. if the contingency is expected to disappear and the situation does not entail any significant risk), attempt a procedure for *contingency resolution* (which may imply diverting from the original flight plan in the expectation that the nominal flight can be later resumed), *UAV recovery* (with implies aborting the mission in an attempt to safely retrieve the UAV operating in degraded mode), *emergency landing* (at the nearest available emergency landing facility) or *flight termination* (which might imply sacrificing the drone to avoid greater safety or security consequences).

   For instance, in case of LoS, the UAV shall always trigger the corresponding Collision Avoidance (CA) response, which may or may not involve the remote PIC intervention, depending on the criticality of the situation. In other cases, such as in well-conditioned situations where the contingency is assessed to be not as critical as to immediately require an abandonment of the UAS mission and initiate vehicle recovery, less drastic contingency management procedures might be applied. As related to LoL, for example, some degree of freedom might be given to the UAV to autonomously try and recover CNPLC performance. In effect, temporarily increasing emission power or switching to an alternative channel (frequency diversity) following a pre-established plan might help regaining CNPLC performance. Another possibility is to maintain trajectory execution as planned during a pre-established amount of time, which might introduce enough spatial diversity to fix the problem. If more spatial diversity is needed, a specific link recovery procedure might have to be executed, which might consist on redirecting the UAV to a pre-established link recovery point or gaining altitude or both. As related to other contingencies such as LoE or LoC it may neither be any chance for the UAV to continue executing its planned trajectory nor for the remote PIC to effectively intervene to handle the situation. In these cases, an emergency landing or a flight termination autonomously conducted may be the only options available.

3) When the contingency is considered critical enough (e.g. unacceptable degradation of performance resulting in the inability to cope with any further potential issue if or a diversion from the approved flight plan is needed to cope with it) the contingency situation must be immediately alerted to all concerned parties, including the RPS, ATC or U-Space traffic management services and the surrounding AVs, through the available communication channels. Ideally, the contingency alert should be accompanied with the relevant information about the characteristics of the problem and the specific way in which the UAS is handling the contingency (e.g. how the AV position uncertainty is expected to evolve as a result of a LoG, UAV operating autonomously as a result of a LoL, etc.).

4) Finally, when diversion from the approved flight plan is needed to cope with the contingency, it is paramount to ensure that the behaviour of the UAV – i.e. its trajectory, remains predictable to all concerned parties in the operational picture. Ideally, the predicted contingency trajectory should be shared by either the RPS or by the UAV itself if operating in LoL (e.g. through the traffic control link). However, situations can be anticipated where the contingency trajectory is

not predictable or it cannot be shared, which poses several challenges that still need to be addressed.

Which levels of criticality are considered enough to raise warnings or alerts, which U-Space should be issued which notifications, whether previously issued warning or alerts may be deactivated and when, which contingency management procedures should be applied in each case, etc., it all entails a large variety of considerations, including technology capabilities, safety and risk, human factors, etc. whose elucidation will require significant further research. Nevertheless, it can be anticipated that different operational contexts as well as different UAS and missions will have different contingency management requirements. As indicated in §4.4.1, the capability-based schema needs to formalize the different contingency management capabilities in a standardized way. Furthermore, as explained in §4.8.1, a particular contingency management logic may be tailored to a specific instance of flight plan. Thus, a prerequisite for the contingency management logic is that its casuistry can be pre-determined at planning time so to avoid UAVs behaving non-deterministically as a result of contingencies.

4.8.5 Flight data recording

The importance of incident/accident investigation in civil aviation is widely recognised. Official investigations of causes and consequences of these safety events and the resulting recommendations are paramount to build experience, learn lessons, prevent that the same mistakes are made again and envisage solutions to new issues discovered, thereby helping to continuously improve aviation safety. In U-Space a similar approach should be adopted, though, additional security and privacy concerns make it likely that investigations need to be extended to these additional aspects of concern.

To support this goal, all flight-related information relevant to safety, security and privacy, such as the actual trajectory flown, milestones reflecting changes with regard to the original flight plan, status of the critical airborne and ground systems, etc., would need to be continuously recorded by the drone operator during the flight as evidence in case of the corresponding investigations. In principle, the flight data recording requirements may vary depending on the operation category, UAS type, airspace and nature of the mission. While in simple operations deemed not to entail any significant safety, security, privacy or environmental concern the need to record flight-specific data may be reduced to a minimum or even exempted, more risky ones from the perspective of the mentioned concerns shall be subject to more strict data recording requirements. At the highest end, recording of specific flight data might even be required to be performed by a certified onboard *flight data recording system* analogous to the ones in use in manned aviation, designed to survive severe accidents in order to support applicable investigations.

In manned aviation, flight data recording (possibly including cockpit voice recording) is mandated by ICAO as part of the MEL (Minimum Equipment List) for aircraft with a MTOM over 5700Kg for which the individual airworthiness certificate is first issued after January 1st, 2005 [93]. However, as it relates to UAS, in view of their inherently higher safety, security and privacy concerns, flight data recording is likely to be mandated more broadly though possibly subject to less strict technical requirements in order to avoid compromising affordability.

Recorded flight data may also become relevant to ensure compliance with insurance terms and conditions, which may drive additional requirements.

Besides enabling investigations, systematic flight data recording would facilitate the application of modern machine learning techniques that exploit massive data to derive knowledge and improve operations in unprecedented ways.

4.9 Traffic

4.9.1 Traffic planning

Near-term UAS operations will most likely take place in segregated airspace. Since airspace is a shared resource (with manned aviation), the airspace segregated for UAS operations must be released as soon as the corresponding UAS mission that was allocated such piece of airspace is over. As a minimum, a UAS traffic planning service should handle airspace allocation (segregation and release, e.g. through a geofencing mechanism). If multiple UAS operations can be planned by different UAS users, needs will arise for more sophisticated UAS traffic planning in order to ensure fair and prioritized access to airspace and adequate balance between the demand of UAS operations within a given airspace and the capacity of the resources in charge of managing its execution so to avoid congestion issues.

Future traffic planning services in the context of U-Space shall assist concurrent flight planning by multiple drone operators to ensure i) availability of access to airspace, ii) adequate balance between system capacity and demand of UAS operations, and iii) fair and prioritized access to airspace.

Such services shall coordinate with the airspace management authority (ATM) the allocation of segregated airspace and the emission of the related NOTAM and operation authorization (OA) when applicable; the service shall prioritize the requested access to airspace based on a well-established prioritization policy and provide feedback to the requesting drone operator on airspace and timeframe availability to re-schedule the requested mission.

A flight plan must be submitted by the U-Space user and approved by U-Space flight planning services before the drone flight can take place. As explained in §4.8.1, such FP defines the nominal flight trajectory with certain level of fidelity, as well as incorporates a companion contingency plan according to §4.8.3. Although a logical step, the *flight approval* process is not as simple as it may seem. As discussed in §4.1.1 multiple UTM providers and/or agencies might potentially have the authority to manage airspace or, perhaps, at least have a say in certain drone operations in a concurrent manner. If a proposed route of a drone passes through a number of airspace restrictions, or managed areas (e.g. including border crossing), the flight plan might have to be approved by all relevant authorities along its entire route before the drone can be issued with a clearance.

One possibility is that a centralised service – let us call it *orchestrator*, oversees all UTM activities and to enforce a common ruleset that all UTM service providers must adhere to. A simple example of this could be a blue light flight operation (whether manned or unmanned) having priority all over other drones operating in a certain context. It is likely that the blue light operation would follow a short notice and, thus, a the centralised authority would need the mandate to change the drone traffic patterns quickly, perhaps forcing some drones to land so the blue light operation can safely take place. This is just a very simple example of what a centralised system might have to deal with.

Again, rerouting a drone for the sake of meeting airspace constraints or maintaining separation is not as straight forward as it might first appear. The centralised service would have to take into account the type of drone, its capabilities and performances, airworthiness certificate, licenses, insurance, etc. The centralised system would need to manage or be closely integrated with the registration services proposed in §4.4 to ensure a drone only operates in the airspace where it has the all the capabilities and permissions to do so. However, the qualified PIC (or the UAS itself, if operating autonomously) should have the last say on whether the given rerouting results feasible. For example, the centralized authority might prescribe a rerouting to a drone, which turns out not to be doable because the drone has not enough fuel/energy or is operating in degraded mode. This is consistent with the assumption that the flight responsibility, accountability and authority lays on the operator side and cannot be handled over to anyone else.

With any change to a drone's route, it is fundamental that the corresponding flight plan is updated. Updating the flight plan is the only process by which the UTM can keep 'situational awareness'. This approach is very different to manned aviation; if a controller changes the heading or flight level of an aircraft, or forces a minor reroute, a new flight plan is not necessary as long as the aircraft is basically following its flight planned route. The reason being, the controller has the use of a radar to maintain situational awareness. UTM is very different as there is no human-in-the-loop to maintain situational awareness on the traffic management side, therefore the UTM service must be kept up to date with any changes made to the intended trajectory, whether this is a minor heading or altitude change. Changing any aspect of flight will require a change or update to the drone FP. In some situations, the UTM system might automatically propose a new flight plan, but an act of negotiation will be needed between the drone operator and the UTM system to ensure that the drone is able to carry out its mission or have to return to base. Any separation assurance or scheduling or sequencing intervention by UTM that changes the intended trajectory of the drone regardless of how minor the change is, will require an update to the flight plan so the UTM maintains control of the airspace.

As touched upon above, knowing type of drone and its *capability level* is a method that could be used to ensure drones and airspace access criteria are managed safely. As indicated in §4.4, Capability Levels should specify, in particular, contingency management capabilities.

This model would allow industry to look to build and certify devices to meet these capability levels with no constraints on the technology that they are allowed to innovate with; a key and fundamental concept in the rapid adoption and rollout of new technology but one which, crucially, can be paired with a geographic restriction and a set of regulatory patterns to match.

Capability levels, therefore, could apply to both hardware and software services; they allow us to define a region where a drone will only be given permission to fly if it meets a certain capability level, and is using services that are built to an appropriate standard, thereby facilitating the automation of flight approval processes.

4.9.2 Flight plan conformance monitoring

A key assumption in U-Space is that the approved flight plan becomes the *contract* between the drone operator and the UTM services. This means that the concerned drone must execute the trajectory described in the flight plan within the uncertainty limits that correspond to the specific approach used to construct such trajectory.

As explained in §3.8, the choice of trajectory modelling primitives and the level of detail they convey largely determine the uncertainty associated with the prediction of the 4D position (the position in space and time) of the AV along its planned trajectory. Also, there are cases where the trajectory cannot even be described at planning time because it is mission-driven. In such cases, large volumes of airspace, perhaps moving and changing shape may be needed to bind the uncertainty about the 4D position of the AV. Drone navigation capabilities and atmospheric/weather conditions may largely influence the 4D position uncertainty as well.

Anyhow, separation minima account for the fact all the uncertainties around the predicted 4D position of the AV at any time are safely bounded by means of a known containment volume. This implies that UTM services – and perhaps neighbour AVs heavily relay in the drone 4D position being always be contained within such containment volume as long as the drone keeps executing its approved trajectory as planned, based on the declared capabilities. Since breaking this contract without prior notice (e.g. declaring a contingency or requesting a flight plan change) might critically compromise separation, a *flight plan conformance monitoring* service results necessary to provide an independent inspection of whether the drones are effectively executing their trajectories to the approved plan.

In essence, what such service does is to continuously compare the 4D position of each AV as 'predicted' on the basis of the approved flight plan in force with the corresponding 'actual' 4D position as observed by the *traffic surveillance* service available (§4.7.1) and trigger a '*FP non-conformance'* alert if the difference exceed the limits of the containment volume.

This way, all concerned parties have an opportunity to safely react to the non-conforming drone.

4.9.3 Traffic control

In analogy with the ATC service of manned aviation, a UAS Traffic Control (UTC) service – also referred to as DTC (Drone Traffic Control) is required to ensure a safe, efficient and fair execution of drone traffic within U-Space. The term 'traffic control' makes real sense when the trajectories of multiple AVs have potential to interact in space and time or, in other words, when two or more AVs operating may become closer to each other than the minimum separation considered safe (*separation minima*). The predicted loss-of-separation (LoS) is referred to as a *conflict*. If not resolved, a conflict has significant probability to develop into an actual LoS, whose result can be a *near miss* – if lucky, or a *collision* in the worst case. As it relates to UAS, the last resource or *safety net* to avoid an actual LoS to develop into a collision is the Detect and Avoid (DAA) capability.

Conflicts are more likely to appear in operational contexts characterized by significant density of traffic or by converging traffic patterns – i.e. when multiple AVs approach a common location, as it happens within airports and their surroundings (e.g. terminal manoeuvring areas, TMAs). As related to U-Space, this situations are likely to occur in urban or suburban environments, as well as near Drone-ports.

Conflicts and LoS can happen in both airborne and ground operations and, in the first case, they may involve the infringement of either vertical or horizontal separation.

It is likely that U-Space adopts a hierarchical approach to how separation is managed analogous to the one existing in manned aviation. This means UTC providing *separation assurance* in a larger time horizon, and DAA coping with *collision avoidance* in a shorter term. As it happens in ATM, in some contexts separation might be delegated to the U-Space users (so-called *self-separation*) on the basis of a sort of *Remain Well Clear* (RWC) approach that is being specified as part of the DAA capability.

Another key assumption is that UTC will most likely have to be a fully automated service. Automated traffic control has been and is still being the subject of extensive research in ATM, which brings the opportunity to leverage a considerable amount of knowledge and lessons learnt onto the UTM realm.

UTC is primarily concerned with *separation assurance*, which consists of detecting and resolving conflicts so to prevent actual LoS to happen. To that end, the future positions of all the AVs participating in a certain traffic scenario need to be known within, at least the time horizon for which the separation assurance function is required. To ensure separation, the position of each AV needs to be circumscribed by a *protection volume* whose size depends on the separation minima applicable in the particular situation.

As explained in §3.8, separation minima depend on many aspects concerning the *flight* (navigation accuracy, trajectory definition primitives used and level of detail, atmospheric conditions, aircraft performances, etc.). But, furthermore, separation minima also depend on numerous aspects concerning the *traffic* - i.e. relative to each other AV, namely, the MTOM and wake vortex of the AVs, their speed and manoeuvre state, the knowledge about their flight/trajectory intent, etc. A major challenge is identified here regarding the need to develop a thorough yet reasonably simple approach to separation minima for U-Space.

Thus *conflict detection* relates to predicting intersections among the protection volumes of all AVs within the given traffic system and *conflict resolution* deals with amending the trajectories of certain conflicting AVs to make the detected conflicts disappear.

The first step (conflict detection) is all about predicting AV positions, applying safe separation minima and efficiently checking protection volumes against each other. Its performance is measured in terms of false (conflict) alerts and missed (conflict) alerts.

The second step (conflict resolution) involves a great deal of complexity, since:

- It requires selecting a framework of primitives used to amend the trajectories (e.g. lateral path constraints such as vectors, path-stretching or rerouting, vertical path constraints such as maximum climb/descent, altitude hold or required altitude, and speed or time constraints) that the flight management counterparts need to be able to understand and comply with; hence a great interoperability challenge.
- It involves close interaction between UTC and the flight management capabilities of the AVs involved in the conflict – which implies safety-critical communications
- The conflicting AVs may not be able to accommodate the flight constraints issued by UTC; which might lead to unsafe situations unless some iterative approach ensures acknowledgment
- The game entails *prioritization* and *fairness* issues

In converging traffic environments, UTC shall also have to be concerned with automatically handling the so-called *merging*, *sequencing* and *scheduling* problems. These problems appear when two or more AVs try to reach the same location at nearly same time (*merging conflicts*) and there on follow the same trajectory. Thus, in this case UTC has to amend the AV trajectories to ensure that separation not only is met at the merging points, but it is maintained downstream, thereby avoiding so-called *catching-up conflicts* that happen when the trailing AV in a sequence gets too close to the leading one. A couple of important aspects of these problems are:

- Conflicts are no longer sporadic nor may be resolved pairwise. In fact, in highly dense traffic environments conflicts can create tightly coupled networks which lead to domino effects (i.e. a conflict between two AVs cannot be resolved independently from the others and/or from causing new ones)
- Traffic *throughput* needs to be maximized as to achieve as much capacity as possible, i.e. separation not larger than exactly the minimum separation is desirable

In the situation as it stands today, the UTM must provide information to allow the pilot to discharge their responsibility to maintain safe separation. Thus the UTM service is not legally required to provide separation assurance. However, as soon as filing a flight plan becomes mandatory, legacy

UTM solutions will be able to provide strategic separation at planning time but not tactical separation, at least in regard of their current maturity.

For a UTM solution to assure separation, the drone industry would require a set of standardized operating procedures for drone operators and UTM system to follow, having a fully comprehensive air picture and full control of all activities taking place within its area of responsibility. In addition, UTM system must have knowledge of the intent of all drone operations taking place within such area.

4.9.4 Traffic data recording

As with flight data (§4.8.5), traffic data recording is also required for safety investigations. Since UTM services will have many safety-critical interactions with many other U-Space actors, all the corresponding safety-relevant information will need to be recorded. Security, privacy and environmental concerns also apply here, although UTM services are assumed in principle not to be potential infringers of the corresponding regulations.

As previously stated in the European ATM Master Plan, “RPAS operations must not degrade the current level of aviation safety or impair manned aviation safety or efficiency”. For this to happen we must make sure that any accident can be properly investigated and that all *decisions* made by a UTM can be properly analysed, not too dissimilar to how it is done in manned aviation. Understanding the volumes of data which could be collated is important, and again we should look at manned aviation. As a reference, the volume of data currently being downloaded and recorded per flight from each modern aircraft (Boeing 787) is 1 Terabyte. Once the data has been recorded, security of the data would be paramount, ensuring the data recording system is tamper prove and only accessed by the appropriate authorities.

In addition to supporting incident investigation, the massive traffic data recorded can provide additional benefits. For example, airspace modelling for improving efficiency, understanding the impact of changes to rules of the air; simulate rule changes and study the impact. Again, modern machine learning techniques might exploit this data in unprecedented ways.

Needless to say, recording all the drone data would be easier to manage if safety-critical decision making was carried out by a centralised system, a single overarching authority coordinating airspace activities and UTM service providers.

4.10 Mission

4.10.1 Mission planning

In legacy UAS solutions mission planning typically reduces to single-UAV waypoint-wise trajectory planning. The mission planning process is performed by the GCS in close coupling with an inherent flight planning capability and in isolation with respect to the possibly conflicting missions being planned by other GCS instances.

Future mission planning capabilities in the context of U-Space shall provide automation support to mission design/re-design for single and multiple UAV missions based on the trajectory modeling capabilities supplied by a flight planning function or service (§4.8.1) not necessarily built-in, considering its feedback on the trajectories being planned to ensure *safety* (e.g. trajectory feasibility, availability of CNS services and airspace allocation, terrain & obstacle clearance, etc). To ensure mission feasibility and other QoS aspects, a modern mission planning service shall consider the performance characteristics (capabilities and limitations, from §4.4.1) of the UAV platforms and payloads to be allocated to the mission, as well as all context information relevant to the mission (e.g. weather conditions from §4.3.1 & §4.3.2), likelihood of interactions with other UAS simultaneously operating in the area, etc). For single UAV missions, the mission planning service shall output a plan that includes the *flight plan* (i.e. the trajectory intended to be flown) along with the specific tasks to be performed by the onboard and ground mission execution resources in coordination with the trajectory execution resources. If the execution of the mission involves human operators, the mission planning shall make provision for their availability. For multiple UAV missions (e.g. formation flights or collaborative missions involving several UAVs or missions involving several consecutive flights), the service shall output a consolidated plan that breaks down into the specific mission plan for each single UAV; when dynamic mission re-planning is required upon mission, flight or traffic execution events, mission planning shall interact with flight planning to safely accommodate mission plan changes that involve trajectory changes.

Mission planning shall also have to interact with U-Space to share relevant mission-specific details that U-Space should be aware of, such as the purpose of the mission and the nature of the payload[47] being carried in (e.g. people, load, sensors, etc.) and its operating status (e.g. in the case of a sensor, whether it is on – i.e. acquiring data or off – standby). Besides other legal implications[48], this information might drive important operational decisions on whether the designed mission can be approved in a given context, ad-hoc restrictions need to be issued or other special provisions (e.g. special contingency or emergency measures, priority changes, etc.) need to be adopted, which in turn shall have to be accommodated by the mission plan.

In addition to the abovementioned interactions, another key aspect of mission planning is to interact with *insurance services* (§4.11.3) to ensure that appropriate insurance coverage is granted for the mission at an affordable cost, based on the risk[49] of the operation being planned. This can be an iterative process, and the insurance certificate obtained may have to be submitted to U-Space traffic services as a precondition for the planned mission to be approved.

4.10.2 Mission execution and conformance monitoring

In legacy UAS solutions, mission execution is performed jointly by the GCS and the onboard autopilot and payload. Essentially, in current systems, mission execution is undistinguishable from flight execution except for the fact that mission execution also covers payload management and control and, possibly, some sort of sensor/mission data processing. No formal mission plan is typically produced by the GCS, so no mission execution conformance to plan – e.g. for the sake of fulfilling

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[47] For instance, the mission plan for an autonomous air taxi should specify in which legs of the flight trajectory the vehicle is empty and in which ones there are passengers on board. Likewise, the mission plan for a UAV intended to spray chemicals (e.g. pesticides) should annotate the volume of product remaining on each leg of the flight trajectory.

[48] Analogous to the *cargo manifest* or the *bill of landing*, or the *passenger manifest/list* in case that the drone transports people on board (e.g. air taxi)

[49] The operation risk should consider all possible damages to third parties: people or property on the ground, other airspace users, people on board if it is a public transport activity and environmental impact (e.g. associated to the possibility to spill chemicals or cause fires)

with or auditing against privacy regulations, can be automatically assessed nor deviation from the plan alerted and/or recorded. Also, most legacy UAS GCS typically cope with only single-flight mission execution.

In future UAS operations in the context of U-Space, mission execution is likely to split, in general, in two pieces of functionality allocated to each one, the ground and air segments. The ground piece of mission execution services shall support rigorous mission execution from the ground segment stand point as per the detailed mission plan produced by the mission planning function (§4.10.1). For each UAV that takes part in the mission, the ground component of the mission execution services shall be in charge of up-linking the mission plan to the corresponding airborne counterpart and activating it for execution. As mission execution proceeds, the mission conformance monitoring service shall continuously analyse available mission and flight data to monitor mission conformance to plan, working in close loop with the airborne mission execution capability and the ground flight execution capability to determine if mission re-planning needs to be triggered e.g. as a result of either (endogenous/exogenous) flight safety or mission related events. The service shall alert on and record mission non-conformities and decide whether to continue the mission or abort it in view of the situation. The service shall interact with and provide automation to the mission operator, who is likely to hold the decision-making authority until more advanced autonomy solutions become available. Mission execution authority might be overridden by the airborne mission execution autonomous decision-making capability in special contingency situations. Conversely the ground mission execution services may provide the mission operator with the capability to manually override the behaviour set by the corresponding airborne piece (e.g. manually operating the pointing and zoom level of an onboard vision sensor to look at some specific feature).

The airborne mission execution capability shall support rigorous mission execution from the airborne segment stand point as per the detailed mission plan feed by the corresponding ground mission execution function. Feed with the onboard processed sensor data, the airborne mission execution service shall supply all the necessary automation in payload management and control for the payload to fulfil its assigned mission tasks (e.g. automatic scanning patterns, zoom/field-of-view adjustments, switch on and off sensor data streaming upon, respectively, entry and exit mission-relevant legs of the trajectory, automatic sensor pointing to track selected targets, reporting PL health status, etc). In general, the airborne mission execution piece shall interact with the airborne navigation function (§4.6) to access aircraft state information (position, speed, attitude, etc), which may be relevant to payload performance. It shall also interact with the airborne flight execution capability (§4.8.2) to i) get updated on whether the flight plan proceeds as planned or any contingency manoeuvre has been activated, which requires making mission-related decisions (e.g. resume or abort the mission), ii) listen to relevant trajectory execution milestones, and iii) request the flight management function (§4.8.2) to engage/disengage autonomous flight modes conceived to support missions that require dynamically changing the flight trajectory.

In particular, the mission execution services shall make sure that special constraints imposed by U-Space on the mission (e.g. switching off the payload upon entering a privacy-sensitive area) are met. Mission execution may be also be required to report specific milestones to U-Space as they are reached (e.g. passenger boarding/unboarding, or special cargo load/unload, entering/exiting specific areas, etc.) since they may affect how the operation is managed by U-Space.

4.10.3 Mission data recording

Besides recording any mission-specific data that drone operators are interested in for their own purposes, all mission-related data that is relevant to U-Space for audit trail purposes[50] shall have to be recorded by the drone operator responsible for the UAS operation and made available to U-Space authorities upon request.

Analogously to with flight data recording (§4.8.5), the mission data recording requirements may vary depending on several aspects, among them the nature of the mission. Again, for simple ones deemed not to entail any significant concern the need to record mission-specific data may be reduced to a minimum or even exempted while more risky ones from the perspective of the mentioned concerns shall be subject to stricter data recording requirements. At the highest end, recording of specific mission data might even be required to be performed by a certified onboard *mission data recording system*, designed to survive severe accidents in order to support applicable investigations.

In manned aviation, only flight data recording is mandated for aircraft above certain MTOW. However, as with flight data recording (§4.8.5), as it relates to UAS, mission data recording is likely to be mandated more broadly though based on low-cost solutions.

Finally, recorded mission data may also become relevant to ensure compliance with insurance terms and conditions, which may drive additional requirements.

4.11 Administrative

4.11.1 Law enforcement

Possible infringements of U-Space rules and regulations in force are more than likely to occur. Consequently, the U-Space system needs mechanisms that allow the relevant U-Space authority to enforce the law through means of discovery and penalisation of violations. Ergo it is necessary to set up a connection with the digitalized regulations of drone traffic, tracking (traffic surveillance) mechanisms, historical records and the Drone and Drone Operator registry services to identify such issues. The list of possible links could be extended by a more detailed research of the future rules of drone traffic and various traffic and operation parameters, which can be captured in a data management system. Since this is still the subject of ongoing and future research, the following table is limited to the already mentioned examples.

This system requires interactions with the designated *U-Space Authority* (expectedly a national authority), the *U-Space* system and *DTM* or *third-party* tracking service providers to ensure accountability of the *Drone Pilot/Operator* under the law and to assure that (national) *Law Enforcement* entities have sufficient data available to perform their jobs.

Field Name	**Description**
Regulations	Digitalized set of rules
Tracking information	Tracked movement of UAS
Historical records	Stored information about tracking information, types of operation and drone equipment as well as previous infringements and sanctions applied

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[50] i.e. to support auditing whether the mission was conducted according to applicable laws and regulations and, in particular, whether it was performed to plan or any deviation has happened

Field Name	**Description**
Operator ID	Unique operator identifier
UAS ID	Unique UAS identifier
Pilot ID	Unique PIC identifier
Issue	Detected infringement
Penalisation	Associated penalisation
Notification	Notification to the infringer including date, time and digital signature of the issuing authority

Table 19: Data requirements for facilitating law enforcement in U-Space

Drone flights will be tracked and the relevant data submitted to the U-Space Authority's historical record storage by traffic management services (DTM or other third-party service provider) with access to it. As with the 'Drone Registry', 'Drone Pilot Registry and 'Drone Operator Registry', the U-Space Authority must assure maintenance, integrity and currentness of data provided in 'Historical Records'. Law enforcement has the right to petition all data relevant to the prosecution of the law from the U-Space Authority. However, such petitions should be managed by a dedicated U-Space '*Data Management System*', which is in charge of providing all relevant information to the petitioning entity (in this case Law Enforcement). In the case of petitions concerning accountability of a Drone Operator/Pilot, the Data Management System will have access to the Drone Registry, Drone Pilot Registry, Drone Operator Registry and Historical Records databases. Furthermore, any submissions of information about previous violations by Law Enforcement will also be managed via the Data Management System, which will store this information in the U-Space Authority's Historical Records. Figure 15 outlines this process.

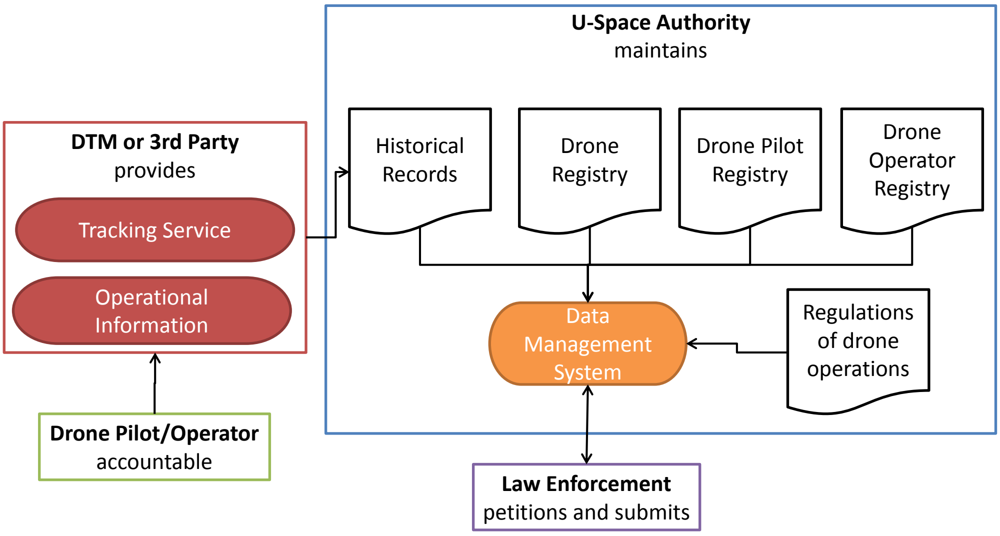

Figure 15: Stakeholders, roles and information involved in law enforcement

4.11.2 Reminders, warnings and alerts

Reminders, *warnings* and *alerts* are usually issued to notify the *concerned addressee*(s) about significant *changes* with regard to the *expected or assumed state or behaviour* that may have an important *impact* and may require *course of action* by such addressee(s). As opposed to reminders or warnings, which denote that the change can be somehow expected or it has not yet occurred, or its impact is less likely or less critical, or the course of action is less needed or less urgent, *alerts* in aviation typically imply that the change is unexpected, disruptive, impactful and requires immediate course of action.

Regarding operational alerts flowing between drone operators and traffic management services as related to in-flight contingency/emergency situations (§4.8.4) as well as flight plan conformance monitoring (§4.9.2) and separation assurance (§4.9.3) processes, there is no doubt about their *alert* nature or who are the issuers and the recipients (addressees) of the alerts. However it is not that clear if other operational alerts related to critical aeronautical or geospatial information updates, or adverse meteorological conditions should be issued by the corresponding services (§4.1, §4.2 and §4.3) or, since they are largely UAS and operation-specific and imply operator workload, it would be more appropriate that such alerts are instead issued by the traffic management services. In effect, traffic management services know enough about the specific details of drone operations being planned or already in execution, UAS characteristics, operational status of the traffic, etc., to filter out who should be issued which of these alerts and when. In addition traffic management services already handle other critical operational alerts. A more decentralized approach might advocate that each drone operator – who obviously knows as well the details of their operations, should be given freedom to rely on the aeronautical, geospatial and weather services of their choice and contract with them which alerts they should be concerned about. In any case, important harmonization and liability issues need to be addressed.

Besides the operational alerts mentioned, there are many other announcements that different participants in U-Space should be notified to with the purpose make them aware of a variety of circumstances of diverse nature not directly concerned with the safety of the operations. A preliminary (non-comprehensive) list of them follows below:

- Pre-flight: expiry of license, validity of technical inspections or insurance; revocation of previously approved mission plan because of changing circumstances; notification of regulatory changes, changes of terms and conditions, taxes or charging policy or prices; expiry of payment periods, expiry of digital certificates/signatures/passwords, etc.
- In-flight: transfer of U-Space responsibilities, e.g. upon border crossing, issuance of additional mission constraints, changes of prioritization in the use of the airspace, mission non-conformance, approaching no-drone zone, imminent breach of law, trespassing of prohibited airspace volumes, environmental alerts, special off-nominal circumstances (etc. catastrophic events, volcanic ash, fire, smoke, toxic spill), etc.
- Post-flight: suspectedly misconducted operation (e.g. safety, privacy, security or environmental infringements), investigation initiated, cumulative number of non-compliances or infringements exceeding a threshold, revocation of license, etc.

One important circumstance that may occur is the loss of a UAV with or without prior notice of an emergency situation being experienced. Depending on the operational circumstances, it may be the drone operator or the traffic services who first realize about the lost UAV event. In any case the situation should be notified to a sort of Alert service analogous to the one in place in manned aviation, which would in turn alert all the rest of concerned parties, emergency services, search and rescue services and accident investigation authorities, as applicable. This will be of special importance when the drone transports passengers or special cargo. As in manned aviation, drones conducting certain types of mission might be required to embark a sort of standardized *Emergency Location Transmitter* (ELT) to facilitate its localization in case of accident.

4.11.3 Risk and insurance

The obligatory insurance of the commercial drone operator for liabilities against third parties (persons and property) is governed in the directive No. 785/2004 of the European parliament and Council, dated 21.04.2004 [94], which governs the obligatory insurances for all air carriers and operators (irrespectively of whether they are manned or unmanned). Its article 2 states that this type of insurance is not obligatory for aircraft with MTOM of less than 20 kg. In other words, all UAVs with MTOM equal or greater than 20 kg must be insured for third-party liability. For the case of lighter drones, the operators are not obliged to have this type of insurance. In practice however, serious professional operators, and increasingly leisure pilots, insure also the operations with lighter drones, with much less than 20 kg MTOM, as such drones do still have the potential to cause serious harm to people or property upon impact.

The adoption by U-Space of a harmonized risk-based insurance approach addressing all operations of UAS of any type and size is deemed paramount. While such an approach is still to be developed, it can be anticipated that the great heterogeneity of potential risks and magnitudes of the possible consequences of accidents involving UAS will lead to significant complexity with regard to the levels of insurance considered acceptable.

A commonly known *per-year* insurance of a single drone or operator activity is generally used in EU, as many insurance companies offer such insurance packages. For instance, in Slovenia, one major insurance company offers third-party insurance up to the amount of 1M€ for the damage to third parties incurred. This insurance business model makes no use of any information services. Traditionally, all administrative work is performed once a year, in advance to individual UAS operations being planned. The insurance premium relies on past, averaged damages, and is not dynamically updated with any quantification of current or short-term predicted risks.

New, modern insurance models are being explored though. These models rely heavily on information services, transferring information from the insurer to the drone user and vice versa. Insurance on *pay-per-flight* basis is starting to be available in UK (for example, Flock, by Allianz) and is planned to be internationally available soon [95]. This insurance covers short-term policies of 1-8 hours duration and has *risk-dependent* pricing. The insurance is executed via a dedicated mobile phone app, in almost real-time (within 30 seconds). The app takes into account several possible risks for a particular drone flight: micro-weather for a specific 4D path or location, ground hazards, inhabited spaces, drone specifications, PIC flight records, etc. and calculates a summed-up risk, so-called *'Flight Risk Factor'*. This factor, as well as all the mentioned separate risks, are presented to the operator on an interactive map. The operator can thus make an informed decision on whether to perform the flight as intended or adjust the flight parameters to de-risk the operation, and thereby lower the insurance price. The insurance can be calculated and assigned for up to ten days in advance.

In addition to enabling the compulsory flight insurance, this kind of insurance increases safety (reduces damage) by nudging operators into lower-risk drone operations.

Thus, *insurance services* are expected to be provided by insurance companies interested in U-Space businesses. These services are likely to interact with *mission planning services* (§4.10.1), as well as with U-Space authorities, and other U-Space services, which may provide specific information relevant to quantify the risk of the specific UAS operation being designed to enable a highly customized computation of the premium insurance, as well as the compliant insurance amount and corresponding terms and conditions.

4.11.4 Special authorization and exemptions

As U-Space progressively evolves, there cannot be expectation about the possibility that its regulatory framework and, thus, the services that realize it at a given moment offer an adequate answer for each and every individual UAS operation need. Thus, it can be foreseen that cases will arise where drone operations need to be conducted in unanticipated circumstances or supported by defective or non-standardized equipment or, in general, present any deviation from the applicable rules. Examples of this can be the use of drones to assists in catastrophes or for experimental purposes or exempted from one or more U-Space rules (e.g. equipment carriage or geofence trespassing) or just in a new use case never explored before. Whether or not such exceptional operations present any exceptional risk of any type, there might exist strong reasons why the operations should be authorized. Not surprisingly, that is essentially the case today – U-Space has not arrived yet, with the so-called *special operation category*, which requires an ad-hoc risk assessment or SORA (Special Operational Risk Assessment) [36].

Just like in some countries COAs (Certificates of Authorization) have been and remain still being a useful instrument to operate UAS in the absence of a more structured framework, it would be convenient that U-Space features a service that allows drone operators filling non-compliances or deviations from the applicable regulations or requesting exceptional drone operations in a harmonized way. In general, approval of exceptional operations shall involve humans making decisions on a case-by-case basis, but at least the service concept proposed would help them keeping track of all related data, speed up the processes and ensure a traceable chain of responsibilities.

This service should initially support the SORA through a standardized methodology for risk assessment as related to drone operations. Down the road, it might evolve towards higher levels of automation in the production and processing of SORA instances, supported by specialized risk assessment tools.

5 Conclusions

The present document (D2.2) is the result of bringing together all the information compiled bottom-up in D2.1 with an analytical effort conducted top-down following the so-called 'domain invariant analysis' methodology. Such methodology pursues achieving a high level of generality in the description of a complex evolving domain subject to great heterogeneity –like U-Space, by formulating the enormous casuistry found in the domain in terms of a few *domain invariants*. These domain invariants capture the essential commonalities among the many dissimilar instances of the domain considered.

The top-down effort was driven by a number of key premises. Chief among them is the idea that the insertion of drones in the airspace is both coupled and synergistic with the ongoing ATM modernization efforts and, thus, a long term perspective needs to be adopted to avoid U-Space 'reinventing the wheel' or at least reinventing it 'entirely'. This means leveraging both successful experiences and lessons learnt in ATM to prevent U-Space from tripping on the same stones that ATM did in the past as the number of drones demanding access to airspace skyrockets in the future. But this also means an opportunity for ATM to essay concepts and, perhaps, leverage experiences, technologies and operational solutions expected to evolve at a faster pace in an environment like U-Space not yet dragged by huge legacies.

To ensure convergence between U-Space and future ATM systems, an effort has been made to maintain coherence between the two realms. To that end, comparisons between legacy and envisioned concepts and solutions across manned and unmanned aviation domains have been profusely made throughout the study, which has led to the identification of commonalities, requirements and design principles, the elucidation of possible solutions to known issues and, also, the identification of new challenges that require further research.

One major conclusion of the effort conducted is that many of the 'apparently' big differences between ATM and U-Space have to do mainly with scale aspects –such as geospatial scales, scale of operational timeframes, scale of heterogeneity in vehicle types, SWAPs, performances, capabilities and limitations, scale of affordability, scale of weather effects, scale of traffic volumes, scale of diversity of operations, scale of automation, etc., not much with the nature of the functions and services involved in the operational picture, which are in essence the same. This has allowed us devising a paradigmatic 'drone operation life cycle' that largely resembles that of a manned aerial operation except for some specificities inherent to UAS.

One key of such specificities is the fact that the pilot, being remotely located, is deemed not to be able to safely handle safety-critical in-flight contingencies, which drives another major conclusion, that is the inescapable need for autonomy; however any autonomous drone behaviour should be deterministic and predictable. It should not come with surprise that flight management autonomy is required for at least contingency management in an environment like U-Space, where fully autonomous traffic management is advocated for capacity and affordability reasons.

Another specificity of drone operations is the concern about security, privacy and insurance issues in addition to safety, which drives the need for U-Space to consider mission-specific aspects of drone operations to the extent needed to cope with such new concerns.

Diverse scale effects make it impossible in general that drones rely on the standard communications, navigation and surveillance (CNS) solutions that manned aircraft use, which drives the need to resort to non-conventional CNS solutions whose performances will play a central role in any capability-based schema that articulates drone access to airspace analogously to the performance-based CNS schema being adopted in manned aviation. Besides CNS, further elements of the capability-based schema are identified and discussed, an important one being contingency management.

Scale effects also require that the aeronautical, geospatial and weather information be significantly more detailed and diverse than the analogous information in use in manned aviation.

A great deal of knowledge, experience and expert judgement available to the IMPETUS consortium went into D2.2 in addition to all the information already compiled in D2.1. This has yield a coherent framework identifying key information needs that U-Space services – as of U1, U2, U3 and, to some extent, U4, will have to fulfil. Moreover, up to 35 U-Space service concepts have been elucidated and numerous of their key aspects have been thoroughly discussed.

However, many aspects though still require much further discussion. Although most of the work on D2.2 was done before the first draft 'Concept of Operations for U-space' [2] CORUS was released, a preliminary cross comparison between both documents reveals a great deal of coincidence, dissimilar – often complementary, level of detail and, also a few discrepancies that will have to be addressed.

An additional objective of IMPETUS is to explore how well the novel *microservices* paradigm and other emerging IT technologies might suit as implementation technology of choice for a number of selected U-Space services. Although D2.2 was initially intended to initiate the technical discussion about implementation aspects, the IMPETUS Consortium has decided to keep D2.2 implementation-agnostic and focused on the conceptual discussion of U-Space services, in the belief that this will facilitate its dissemination and review within sibling U-Space projects, as well as by relevant UAS stakeholders elsewhere.

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Appendix A Technical details of reference

A.1 Recap on UAS insertion issues

It has been argued that the simplest approach to enable UAS insertion in civilian airspace might consist on just making UAS operations *transparent*[51] to Air Traffic Control (ATC) and existing airspace users (manned AVs). That is, basically, the inherent idea underneath the human-centered notion of *Remotely Piloted Aircraft Systems* or RPAS [96].

As the pilot-in-command (PIC) is assumed to be in the loop at all times, in principle, RPAS could operate almost exactly as manned AVs do. However several reasons explain why such an approach cannot work as of today. In effect, because of PIC's remote location:

1) The communication between the ATC officer (ATCO) and the PIC is no longer possible using standard communications infrastructure and equipment (CNS), namely the Air/Ground (A/G) voice frequencies and emerging data links
2) The PIC has worse situational awareness and response times. The number one issue is the loss of the *see-and-avoid* (SAA) function, which represents the means to maintain separation with terrain, obstacles and surrounding traffic when operating under VMC (Visual Meteorological Conditions) as well as the last safety net to cope with a potential *loss-of-separation* (LoS) situations. Another important issue is the inability of a remote PIC to cope with a *loss-of-engine* (LoE).
3) Critical dependency of the PIC-UAV interactions on the Command and Control (C2) link, which leads to the well-known *loss-of-link* (LoL) issue, also including derivate issues such as the inability to notify and manage further in-flight contingencies, as well as cyber-security threads such as *loss-of-Authority* (LoA)

Furthermore:

4) ATC traffic surveillance of UAS is not guaranteed using standard surveillance (CNS) infrastructures such as primary/secondary radar systems (PSR/SSR)
5) Pioneer UAS GNC (Guidance, Navigation & Control) and flight management approaches do not necessarily follow civil aviation standards; in particular, navigation typically depends critically on GPS – which leads to the *loss-of-GPS* (LoG) issue, and flight management, guidance and control follow waypoint-wise (e.g. NATO STANAG-4586 [71]) rather than ICAO DOC-8168 [92] flight procedures supported by ARINC-464 [90]and ARINC-702A [91]compliant systems
6) Higher heterogeneity of AV sizes, performances and capabilities are expected in the airspace if RPAS are granted access to it
7) As UAS operations become business as usual, airspace capacity issues caused by potentially huge traffic densities in some contexts

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[51] 'Transparent to ATC' essentially meaning that the UAV is 'seen' by the ATC surveillance function and the ATC service can interact with the (remote) UAS cockpit in the same way that it does with manned AVs, i.e. as of today through VHF voice and, in the near-future, also via ATS (Air Traffic Services) datalink

8) Except for the certified category, UAS remote PIC is assumed in general less skilled than a conventional pilot

Though the approach of making RPAS transparent to ATC and existing airspace users is rather naïve, it helps drawing the rationale about which are the most important UAS insertion issues from the stand point of aviation authorities and traditional airspace users.

We acknowledge that traffic problems[52] as related to either UAS-only operations or UAS operating in non-segregated airspace imply considerable challenges, which next generation ATM and emerging UTM solutions shall have to cope with.

However, chief among the numerous challenges encompassed by UAS insertion is to guarantee the safe operation of each individual UAV under any operationally reasonable circumstance, including under expectable critical in-flight contingencies, once there is no longer a human pilot aboard. In addition to in-flight contingencies like loss-of-separation (LoS) or loss-of-engine/energy (LoE), which do also affect manned AVs, UAVs, because of their nature, are subject to new ones such as loss-of-link (LoL), and loss-of-GNSS (LoG), as well as, in general, more prone to loss-of-control (LoC).

The need for autonomy in critical in-flight contingency management

As independent events, the five critical in-flight contingencies (LoS, LoG, LoL, LoE and LoC) mentioned above can occur individually or in any combination, giving rise to different severity conditions. Bearing in mind that i) any combination of flight contingencies can happen while already in LoL and, ii) the remote PIC can neither be assumed to have a complete situational awareness nor the response time or the necessary skillset to properly manage contingencies remotely, some sort of *autonomous contingency management* capability on board the UAV is inescapably required to safely handle the variety of contingency situations that can arise.

Such onboard autonomous contingency management function must be able to make safety-critical decisions, possibly leading to recovery trajectories that allow the UAV safely coping with the contingency situations and, to the extent possible, resume mission execution or, otherwise, gracefully abort it (which may involve terminating the flight) without causing an *accident*[53].

Therefore, autonomy in flight management will be, to different extents, inexorably required for, at the very least, contingency management, which challenges the prevailing philosophy advocated in civilian aviation, where UAS are disregarded in favour of RPAS [96], assuming the existence of a remote pilot-in-command all the time (Figure A-1).

Acknowledging the need for autonomy is the reason for the preference of the term 'UAS' rather than 'RPAS' all throughout the present document.

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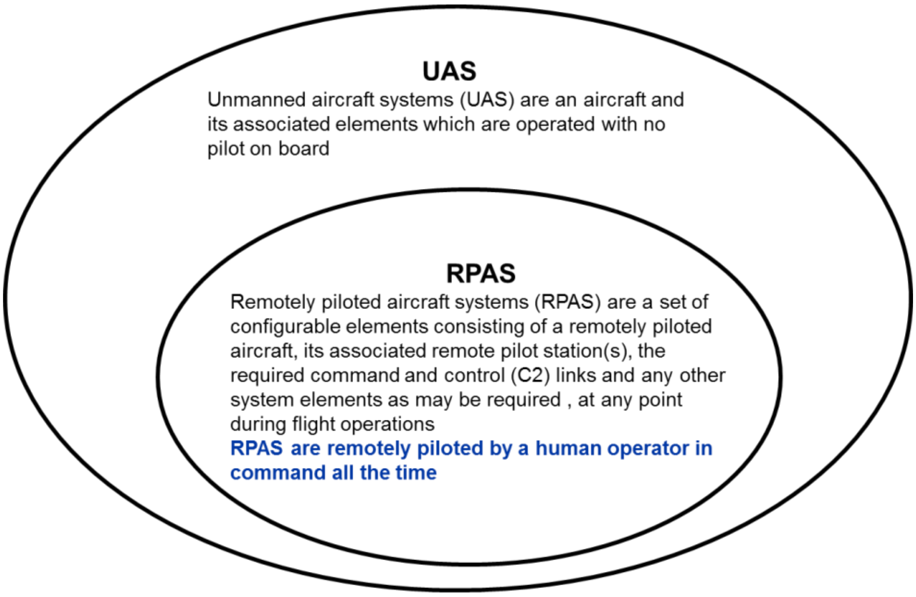
[52] I.e. interactions among AV trajectories, including capacity and demand balance (pre-flight), traffic deconfliction (during flight), traffic sequencing and scheduling, etc.

[53] In aviation, the term 'accident' applies when serious damage is caused to people (serious injuries or casualties) or the aircraft itself (including the loss or the total destruction of the aircraft). As related to UAS, the notion of unmanned aviation accident might have to be redefined, perhaps including the case of slight injuries to third-party people and excluding the case when the UAV results damaged or even totally destroyed as a result of a controlled flight termination.



UAS

Unmanned aircraft systems (UAS) are an aircraft and its associated elements which are operated with no pilot on board

RPAS

Remotely piloted aircraft systems (RPAS) are a set of configurable elements consisting of a remotely piloted aircraft, its associated remote pilot station(s), the required command and control (C2) links and any other system elements as may be required , at any point during flight operations

RPAS are remotely piloted by a human operator in command all the time

Figure A-1: RPAS vs UAS (ICAO circular 328-AN/190)

Besides safety, autonomy will also be a critical discriminator in mission effectiveness and other QoS performance aspects such as affordability, etc.

A.2 Drone identification

Concerning the identification of drones in flight, a report by the Aircraft Owners and Pilots Association (AOPA) [97] stated that the FAA´s Unmanned Aircraft Systems Identification and Tracking Aviation Rulemaking Committee found that drone identification data should at least include the drone's ID, tracking information and drone pilot information. Various approaches to identification of drones are already under discussion. For instance, the FAA proposes two approaches [98]: The first is data broadcast directly from the drone and digitally encoding identification information into the radio signals between the drone and the control station. This is advantageous for local identification of the drone. The drone manufacturer DJI stated in a discussion paper [99] that it has enabled the capability for its drones to broadcast information for remote identification, a move that is aligned with the FAA´s first proposal. The second approach would be to transmit drone data to an internet service during flight. This service could be accessed remotely by law enforcement agencies. Both approaches could be used in parallel, to allow for system wide identification as well as local identification, the latter of which could be very useful in rural areas with little or no cellular or other data network coverage.

The e-identification function is also on the focus of the EASA Opinion No 01-2018 (*Introduction of a regulatory framework for the operation of unmanned aircraft systems in the 'open' and 'specific' categories*) [100]. The opinion states that, for UAS classes C1, C2 and C3, each AV will broadcast both the UAS operator registration number and the UA's unique Serial Number. Besides, security agencies taking part on the EASA consultation process leading to the Opinion development, provided a clear request to equip UAS with a 'local' e-identification system, broadcasting a minimum set of information directly from the UAS over a short range, independently from the capacity of the U-Space services to provide a network identification. Hence, a second method of e-identification, independent from the network, will anyway be required.

In any case, this would require the inclusion of the drone's *e-Identification Number*, which would serve as the point of enquiry within the e-Identification service as well as the *Remote Identification System/Code* in the *drone registry database* to allow for remote identification. In its paper [101], DJI listed various technological possibilities for the remote identification of drones, which will need to be specified in the *Remote Identification* part of the registry. These technologies include: ADS-B, Networked Cellular, Integrated C2, Low-Power direct RF (such as Bluetooth), Satellite technologies and Visual Light Encoding.

A.3 Detect and Avoid

It is commonly accepted that a key pre-requisite to enable safe operations of UAS in crowded non-segregated environments is the capacity to replicate the ability of human pilots to *"see and avoid"* as to guarantee appropriate obstacle clearance and separation with surrounding traffic.

In the domain of manned aviation, the dispositions relative to the avoidance of Mid-Air Collisions (MACs) are established in Annex 2 to the ICAO Convention '*Rules of the Air*' (ROA) [102], while the 'see and avoid' capability is specified in the FAR regulations Part 91 [103]. In such domain, despite the existence of automation systems and collaborative concepts that support the pilot in his function to maintain separation with traffic and obstacles (e.g. ACAS/TCAS, ASAS, TIS-B, etc.) nothing ultimately precludes his responsibility to survey the vicinity with his own eyes and exert the necessary manoeuvres to ensure separation or avoid collisions.

In order to develop an equivalent *Detect and Avoid* (DAA) capability within the domain of UAS several strategies could be considered, which might combine solutions already adopted in the manned aviation realm (e.g. TCAS, IFF, ADS-B) with the use of autonomous sensors such as Radar, Lidar, visible/IR cameras, sonar, etc. This has being explored within some major R&D initiatives oriented to provide a D&A capability for medium and big UAS (e.g. MIDCAS [104] in Europe).

Concerning the *Detect* part, the main drawback of such solutions is that they rely on collaborative information exchange and/or require sensors whose SWAP characteristics result unviable for small UAS. With regard to the *Avoid* piece, the UAV must have the capability to automatically generate *Remain Well Clear* (RWC) and *Collision Avoidance* (CA) advisories (manoeuvres), as well as autonomously execute them if necessary.

To date, a DAA capability for small UAS that renders equivalent performance to the "see and avoid" function performed by pilots' onboard manned aircraft is still to be demonstrated. But, furthermore, in future operational contexts of, expectedly, considerable high traffic density and heterogeneity, such a DAA solution shall have to become even much more sophisticated, as collision avoidance may no longer be decoupled from separation assurance.

Limitations of the Sense and Avoid function

In today's manned aviation context the *sense-and-avoid* (SAA) function is exerted by pilots based on human vision (the perception means), pilot eyes acting as the onboard, *independent* sensor.

The standard SAA solution has several limitations, the most important ones being that it is i) applicable only as long as VMC exist, and ii) subjective to PIC vision and mental process performances. Standard *separation minima* applicable to today's VFR operations assume that an average onboard PIC is able to see an intruder manned AV within the ownship's field of regard (FOR), though no quantitative characterization of such performance has ever been conducted for the large casuistic associated to diverse AV sizes, performances, encounter configurations and human perceptive capabilities. Moreover, as unmanned AVs come into scene, such heterogeneity results largely increased, preliminary research [81] showing evidences that a human pilot setting on board a small general aviation AV would typically be unable to see an intruding 25 Kg fixed-wing UAV until it is too late to avoid the mid-air collision (MAC).

Under instrumental meteorological conditions (IMC), the PIC onboard a manned AV can no longer perform the SAA function, the only certified safety net available in nowadays being TCAS[54] (Traffic Collision Avoidance System), which, essentially relies on a cooperative sensor (the onboard SSR transponder/interrogator) to detect surrounding traffic and, depending on the TCAS function level featured by the concerned AVs, provide a collision resolution advisory (RA) to just the ownship pilot, or both AV pilots (ownship and intruder), should coordination of TCAS RAs be supported.

A.4 Example of flight planning using NATO STANAG-4586

NATO STANAG-4586 [71] has become the *de facto* C2 communications data protocol in many legacy UAS. A key piece of such protocol is concerned with how the mission trajectories (flight plans) built within the RPS are uplinked to the RPA for further execution.

According to NATO STANAG-4586, an Air Vehicle (AV) flight plan is made by one or more routes, each of them composed by a sequence of waypoints (WPs). Routes, in particular, represent the AV path in a 4D space having the waypoints as vertexes. Fourth dimension is specified assigning speed or temporal constraints to selected WPs. At a given time, the AV is following an active route (e.g. "Sample Route").
As an example, Figure A-2 shows the information related to the trajectory definition (flight plan) of a particular route ("Sample Route"), based on NATO STANAG-4586 (messages #13001 and #13002),

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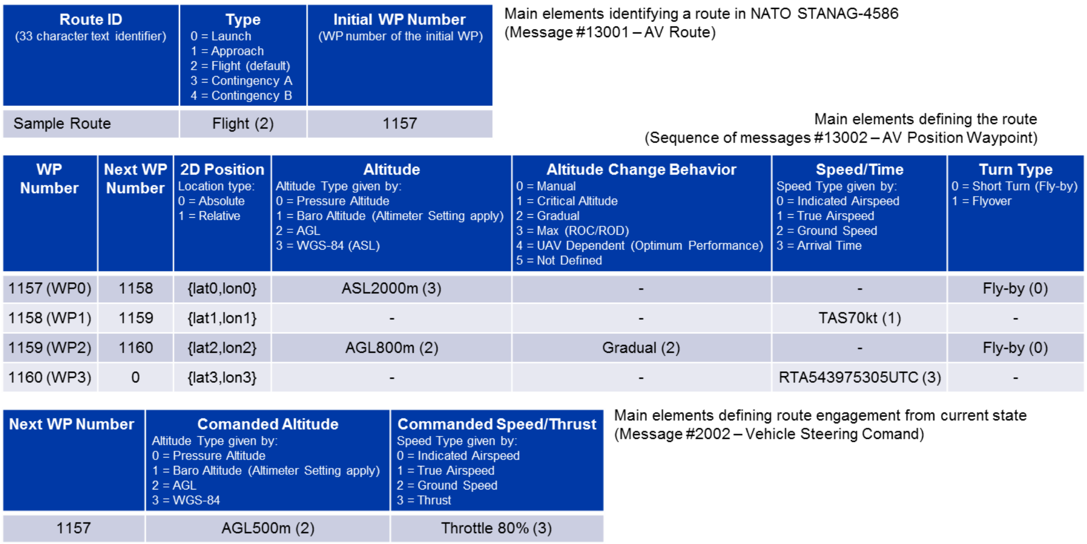
[54] From the regulatory stand point, although TCAS (ACAS) is mandated by ICAO for all aircraft with MTOW of over 5,700 kg (12,600 lb) or authorized to carry more than 19 passengers (CFR 14, Ch I, part 135 requires that TCAS I is installed for aircraft with 10-30 passengers and TCAS II for aircraft with more than 30 passengers), it is important to highlight that TCAS is not taken credit for in the calculation of the Target Level of Safety (TLS) figure of 10^{-9} considered as the acceptable probability of accident in civil aviation.

RTCA Special Committee 147 (SC-147), Traffic Alert & Collision Avoidance System (TCAS) started work on a new Aircraft Collision Avoidance System for NextGen, known as ACAS X. The foundational system to be specified will be ACAS X_A, with the "A" denoting active surveillance. ACAS X_A will be a "drop-in" replacement for TCAS II; expected MOPS completion date – December 2018. One relevant difference between TCAS and ACAS X_A is that the later includes horizontal avoidance manoeuvres while the former does only consider vertical ones.

along with the AV steering command that instructs the engagement of such route from current AV state (message #2002).

Waypoints are the essential trajectory description primitive of the STANAG-4586 mission/flight plan protocol. Waypoints may be defined as 2D/3D/4D points that can contain the following information:

- Waypoint Number (univocal identifier of a WP)
- 2D Position in terms of geodetic {latitude, longitude} referred to WGS-84 or, alternatively, Cartesian {X, Y} coordinates with respect to a relative local Cartesian reference frame
- Altitude in terms of either pressure/baro-altitude or height; in the latter case it can be referred to either MSL (Mean Sea Level), i.e. ASL (Above Sea Level), or the local ground (AGL, Above Ground Level). It is important to highlight that altitude an constraint captured by STANAG-4586 as part of a given WP definition does actually apply to the next WP of the sequence, except if the Altitude Change Behaviour attribute is set to Critical Altitude, in which case a whole spiral up/down flight pattern is inserted at the given WP to ensure altitude adaption locally at such WP.
- Speed: typically relative to wind (airspeed), in terms of Indicated Air Speed (IAS) or True Air Speed (TAS), or absolute speed referred to the ground, i.e. Ground Speed (GS).
- Time: typically a Required Time of Arrival (RTA) to the waypoint referred to UTC (Universal Time Coordinated) time reference
- Turn type: short turn (i.e. Fly-By) or Fly-Over (i.e. fly-through).
- Next WP number: WP number of the next WP in the (route) WP sequence



Main elements identifying a route in NATO STANAG-4586 (Message #13001 – AV Route)

Route ID (33 character text identifier)	**Type** 0 = Launch 1 = Approach 2 = Flight (default) 3 = Contingency A 4 = Contingency B	**Initial WP Number** (WP number of the initial WP)
Sample Route	Flight (2)	1157

Main elements defining the route (Sequence of messages #13002 – AV Position Waypoint)

WP Number	**Next WP Number**	**2D Position** Location type: 0 = Absolute 1 = Relative	**Altitude** Altitude Type given by: 0 = Pressure Altitude 1 = Baro Altitude (Altimeter Setting apply) 2 = AGL 3 = WGS-84 (ASL)	**Altitude Change Behavior** 0 = Manual 1 = Critical Altitude 2 = Gradual 3 = Max (ROC/ROD) 4 = UAV Dependent (Optimum Performance) 5 = Not Defined	**Speed/Time** Speed Type given by: 0 = Indicated Airspeed 1 = True Airspeed 2 = Ground Speed 3 = Arrival Time	**Turn Type** 0 = Short Turn (Fly-by) 1 = Flyover
1157 (WP0)	1158	{lat0,lon0}	ASL2000m (3)	-	-	Fly-by (0)
1158 (WP1)	1159	{lat1,lon1}	-	-	TAS70kt (1)	-
1159 (WP2)	1160	{lat2,lon2}	AGL800m (2)	Gradual (2)	-	Fly-by (0)
1160 (WP3)	0	{lat3,lon3}	-	-	RTA543975305UTC (3)	-

Main elements defining route engagement from current state (Message #2002 – Vehicle Steering Comand)

Next WP Number	**Comanded Altitude** Altitude Type given by: 0 = Pressure Altitude 1 = Baro Altitude (Altimeter Setting apply) 2 = AGL 3 = WGS-84	**Commanded Speed/Thrust** Speed Type given by: 0 = Indicated Airspeed 1 = True Airspeed 2 = Ground Speed 3 = Thrust
1157	AGL500m (2)	Throttle 80% (3)

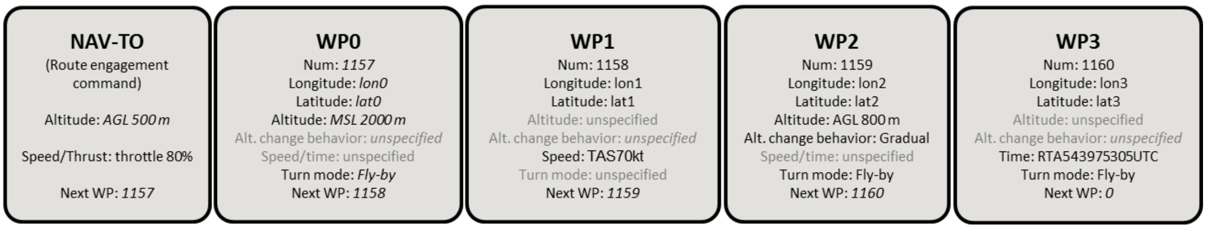
Figure A-2: Information encompassed by a trajectory definition using NATO STANAG-4586

The WP number is used as univocal identifier and it is the key that permits to build the routes. WP number ranges from 1 to 65535. “0” indicates the end-of-route. As a minimum, WP number and 2D position must be given for each WP designed as part of the route, which outlines the lateral path of the route. Further information such as the turn mode can be optionally provided at each WP to capture more detail about the lateral path. Also, further requirements such as altitude and/or speed/time constraints can (optionally) be associated with each waypoint to capture some high-level details about the longitudinal and propulsive profiles, respectively addressing 3rd-dimensional and 4th-dimensional aspects of the AV motion.

A second primitive considered by STANAG-4586 is the so-called *loiter waypoint*, which essentially can represent either a circle of constant radius (also referred to as a Circular Loiter), a hippodrome (Racetrack Loiter) or a 8-figure, depending on the specific parameters that define the loiter pattern. For each loiter waypoint, it is possible to define the Radius, the turn Direction, and the Loiter Time; for the Racetrack and 8-figure it is also possible to define the *Length* and the *Bearing*. All loiter patterns are intended at constant altitude (the altitude of the approaching leg) and speed (speed can be specified for the loiter pattern).

In our example we have defined a simple route plan using STANAG-4586, as a sequence of four 2D waypoints (WP0, WP1, WP2 and WP3), including constraints associated with them, such as altitude reached at the (next) WP (500m, 2000m and 800m), speed/time constraints (TAS 70kt and RTA543975305UTC) and the turn type (in our case all turns are prescribed as fly-by, except turn at WP1, which is left unspecified). The sample trajectory model also includes the route engagement leg from current AV position at the time that the route is activated (NAV-TO).

Thus, as reflected in Figure A-3, a model of the flight plan made in terms of STANAG-4586 would look like a route engagement command followed by a sequence of waypoints, each including longitude and latitude as a minimum plus, possibly, the additional information that capture altitude and/or speed/time and/or turn mode constraints.



NAV-TO
(Route engagement command)
Altitude: *AGL 500 m*
Speed/Thrust: throttle 80%
Next WP: *1157*

WP0
Num: *1157*
Longitude: *lon0*
Latitude: *lat0*
Altitude: *MSL 2000 m*
Alt. change behavior: *unspecified*
Speed/time: unspecified
Turn mode: *Fly-by*
Next WP: *1158*

WP1
Num: 1158
Longitude: lon1
Latitude: lat1
Altitude: unspecified
Alt. change behavior: *unspecified*
Speed: TAS70kt
Turn mode: unspecified
Next WP: *1159*

WP2
Num: 1159
Longitude: lon2
Latitude: lat2
Altitude: AGL 800 m
Alt. change behavior: Gradual
Speed/time: unspecified
Turn mode: Fly-by
Next WP: *1160*

WP3
Num: 1160
Longitude: lon3
Latitude: lat3
Altitude: unspecified
Alt. change behavior: *unspecified*
Time: RTA543975305UTC
Turn mode: Fly-by
Next WP: *0*

Figure A-3: Schematic representation of a STANAG-4586 flight plan

Uncertainty in trajectory representation

STANAG-4586 trajectory description primitives, in general, convey little information about the specific guidance and control laws that can be applied so that the AV motion fulfils the prescribed position, altitude and speed/time constraints. Figure A-4 below shows a representation of the ambiguities (uncertainties) inherent to the STANAG-4586 trajectory description (represented as dashed lines with question marks), which also become evident when trying to depict the 4D trajectory being modelled in a 4D space.

With the limited fidelity of STANAG-4586 trajectory representation, it is not possible to turn the unknown dashed lines of Figure A-4 into concrete continuous ones or without guessing. In other words, though a (discrete) number of constraints have been captured, the specific motion of the AV that fulfils such constraints remains largely undetermined. Thus, different GNC (Guidance, Navigation and Control) solutions typically interpret and, thereby, execute the same STANAG-4586 trajectory model in different ways, giving rise to different AV motion histories. For instance, some GNC solutions might choose fly-by as the default solution for the turns for which the turn mode has not been specified while others might choose fly-over. Furthermore, different GNC solutions implement fly-by and fly-over turn modes in different ways. Similar examples could be brought on how different

GNC solutions implement dissimilar guidance & control strategies to fulfil altitude and speed/time constraints.

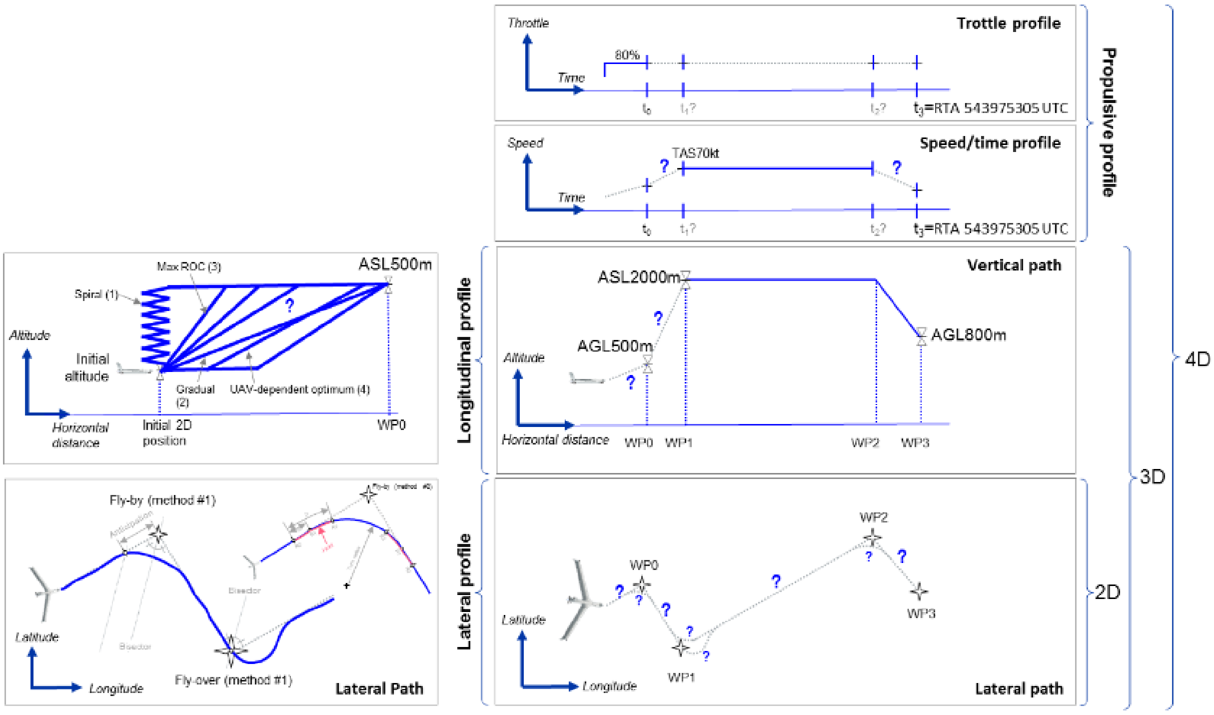


Figure A-4: Ambiguities/uncertainties associated with STANAG-4586 LOFI flight plans

While existing GNC solutions typically do well in the pursue of some sort of optimality, since much of the guidance and control references are implicitly generated on-the-fly, it is hard for third-party actors to accurately predict the 4D trajectories that will result from such low-fidelity flight plans. As a result of the lack of a complete/unambiguous high-fidelity definition of the AV trajectories that needs to be synchronized across the many elements that have a say on them (humans & automation systems), such elements must make assumptions and take decisions in presence of considerable uncertainty with the outcome that safety has to be ensured via large safety buffets in detriment of other performance aspects such as capacity, efficiency and environmental impact, plus automation is greatly hampered. Thus, the optimality achieved by the GNC solution in virtue of the freedom left by incomplete low-fidelity trajectory models very often becomes irrelevant in front of the penalties associated with the trajectory amendments needed to ensure safety (e.g. conflict/collision avoidance) or cope with capacity issues (e.g. holding while in-flight or engines on), ultimately derived from the lack of trajectory predictability.