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Abstract

Advanced Air Mobility (AAM) demands greater levels of aircraft autonomy than are currently implemented today. To enable this requirement, novel aircraft functionalities and technologies as well as supporting airworthiness and operational regulations are required. A structured method to derive a comprehensive list of aircraft level decision-making functions is defined and applied. The resulting function set is programmed into an ontology, and enables autonomous decision-making through the application of a defined decision-making process. Paths to implementing the functions are generated by applying a structured four step method. By surveying current technologies, airspace, procedures and regulations, the paths generation method defines incremental paths to autonomy that the current regulatory environment can support. Opportunities to implement novel technologies and functions are identified, and regulatory mechanisms supporting their implementation are underscored. The analysis provides the tools to further define aircraft functions and paths to their implementation, while demonstrating that for particular use cases, aircraft autonomy is attainable in the medium-term.

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Preamble

The long-term vision for Advanced Air Mobility (AAM) pushes the boundaries of "traditional" aviation into a new era of on-demand passenger travel between rural, suburban, and urban destinations not currently served by conventional air transportation methods. AAM may incorporate elements of Urban Air Mobility (UAM); Single Pilot Operations (SPO); Simplified Vehicle Operations (SVO); and Remotely Piloted Aircraft (RPA). UAM addresses a vision of almost unrestricted personal air-mobility within or between urban environments, potentially with traffic densities substantially greater than existing Instrument Flight Rule (IFR) operations. SPO is intended to address the growing pilot demand and supply gap by reducing the number of required crew, particularly for 14 Code of Federal Regulations (CFR, which incorporates the Federal Aviation Regulations) Part 121 Air Carrier Operations. SVO seeks to redefine the relationship between the pilot and the aircraft, by allocating tasks that are traditionally the responsibility of the pilot to the aircraft automation. RPA would enable M:N (*"M pilots to N aircraft")* operations, where a pilot may remotely control one or more aircraft at a time.

A common and important thread underlying each of these AAM implementations is the concept of vehicle autonomy, where some or all of the traditional "piloting" functions are assigned to the onboard vehicle automation. This immediately raises several challenges:

1. What functions does the human pilot perform?
2. How should these functions be allocated between the human pilot (if any) and the on-board automation?
3. How should the airworthiness and operational aspects of these (newly) automated functions be implemented and certified by the Certification Authorities?

Today's existing traffic management frameworks cannot support the degree of autonomy, traffic density, and trajectory diversity envisaged for AAM, so new operational and certification strategies will be required, as well as new rulemaking. For example, 14 CFR 121.385 requires two pilots for Part 121 Air Carrier operations, so any implementation of SPO would require a corresponding change (or relief from) this regulation. Similarly, 14 CFR 91.3 states *"The pilot in command of an aircraft is directly responsible for […] the operation of that aircraft"* which will require a new responsibility paradigm for unpiloted aircraft.

When applied in the context of the technological and operational innovations required by AAM, the current regulatory tools and assumptions to evaluate new functions, technologies and operations do not provide a complete path to implementation. For example, current certification processes do not provide a path to compliance for non-deterministic Artificial Intelligence (AI) systems; and there is limited guidance for the development of electric propulsion systems, or for developing "pilotless" passenger aircraft. Furthermore, AAM challenges a cornerstone of airworthiness certification: service history. Novel concepts cannot be certified because there is no service history, yet it is impossible to accumulate reliability data without deploying the new system extensively. This leaves the innovators in the difficult position of having to launch a system in a non-revenue context in the hope that sufficient data can be quickly accumulated to achieve airworthiness certification. Without novel certification processes, the defining features of AAM will remain inaccessible to the types of operation that could leverage them.

This paper examines the questions in two parts: the first section addresses the identification and classification of a core set of aircraft functions to enable autonomy. The second section introduces a structured method for creating viable paths to vehicle autonomy, exemplified by its application to the development of four viable candidate automation paths. Each of these sample paths embodies different subsets of the automation functions developed in Section 1, and each path is built incrementally with increasing levels of automation, culminating in a mature AAM system whereby the vehicle operates in its target environment fully-autonomously under all normal and foreseeable contingency operations. The second section also addresses the certification challenges for deploying the proposed paths to autonomy, because no formalized certification basis currently exists for the full transition to mature AAM. The incrementality built into the paths is a key determinant of the ultimate "certifiability" of each proposed path.

Section 1: Functions for Autonomy

Introduction

Complete autonomy can be broadly defined as the centralization of all decision-making functions to the aircraft, which implies that the decision-making process has access to sufficient information to safely make those decisions.

Present day operations are conducted in accordance with Visual Flight Rules (VFR) or Instrument Flight Rules (IFR). VFR provide aircraft the operational flexibility [3] to depart an airfield without filing a flight plan or requiring an Air Traffic Control (ATC) clearance to enter the National Airspace System (NAS). In this mode of operation, according to 14 CFR 91.155 crews are solely responsible for maintaining traffic and terrain awareness visually. By relying on their eyesight, crews are trusted to navigate the environment on their own without ATC supervision, and are therefore operating autonomously. However, this flexibility comes at the cost of accessibility. VFR traffic cannot lose "sight," so it cannot fly through clouds, is altitude limited, and is prohibited from operating in certain airspace classes without meeting minimum equipage and operational requirements (14 CFR Part 91, Subpart B – Flight Rules, General).

IFR operations make available that airspace that is unavailable to VFR traffic. By abiding by IFR, en-route operations can be conducted in zero visibility by relinquishing "sight" to ATC for traffic separation, and adherence to procedures for terrain and obstacle clearance. These constraints provide IFR traffic with the access to all airspace within the NAS (14 CFR Part 91), at the cost of flexibility. To benefit from IFR access according to 14 CFR 91.175, aircraft must be cleared into the Air Traffic Management (ATM) system, follow filed flight plans, fly prescribed trajectories, and comply with Air Traffic Control (ATC) clearances and instructions.

Despite differences in their operational allowances and constraints, both VFR and IFR make assumptions about the on-board decision-maker's knowledge about the environment. The current operational regulations are written around these assumptions, and it is implicit that neither the pilot nor the ATC controller has complete situational awareness (SA) in isolation: VFR operations do not always require communication radios and, with few exceptions, are not required to have on-board weather detection systems. Nonetheless, they are authorized to operate autonomously. In IFR, crews delegate traffic awareness to ATC, which provides instructions without complete knowledge about the vehicle's system health or performance capabilities. In VFR, pilots generate their SA through sight, hearing, experience, and good judgment, while in IFR, multiple agents with partial SA cooperate to generate an adequate overall air picture. As will be shown, this distributed approach, with its attendant compromises, is unlikely to prove satisfactory for AAM applications.

AAM is likely the next major growth sector in aviation flight operations. AAM operators will seek to combine VFR flexibility and IFR accessibility to facilitate very high-density uncontrolled operations while supporting diverse missions that are not supported by today's regulatory framework. To enable AAM, an expansion of "how" and "where" aircraft can operate autonomously is required. To support this expansion, Wing et al. propose a new concept of Digital Flight Rules (DFR) to set the operational guidelines in which *"vehicle operator[s will] assume full responsibility for traffic separation…and trajectory management…in all visibility conditions and airspace regions"* [3].

In this report, the concept of DFR is leveraged as foundational for the functional analysis for two reasons: it defines a new set of flight rules that conceptually meet AAM operation requirements (i.e., flexibility + accessibility), and it requires that complete decision-making authority be exercised at the aircraft. In a crewed scenario, full navigational decision-making authority must then be allocated to the crew, implying it must perform functions that were traditionally the responsibility of ATC. In the context of uncrewed aircraft, a complete analysis of all tasks normally performed by pilots is required so that they can become the automation's responsibility.

The functional analysis which is the subject of this section, assumes an uncrewed aircraft operating under a future regulatory basis of DFR that ascribes operational autonomy (defined below) to the operator. This approach yields a complete set of functions that can then be allocated to cover the spectrum of human-automation crewing combinations. First, autonomy is defined in terms of vehicle functions and vehicle operations; second, autonomy supporting concepts are discussed in detail; third, a method for deriving vehicle functions is provided; lastly, a complete functional breakdown is listed and programmed into an ontology.

Autonomy

In DFR, operators would be entirely responsible for maintaining traffic awareness and for managing their trajectory accordingly. In other words, operators are the sole decision-making entity. This is essentially an expansion of the VFR pilot's responsibilities into the IFR environment. The American Society for Testing and Materials (ASTM) defines *"Autonomous"* as *"[a]n entity that can, and has the authority to, independently determine a new course of action in the absence of a predefined plan to accomplish goals based on its knowledge and understanding of its operational environment and situation."* [1] By this definition, crewed VFR flight operation can be considered autonomous since pilots make independent decisions regarding their trajectory. On the other hand, IFR flights cannot be considered autonomous because pilots do not have "independent" authority over their trajectory. An aircraft that is operated VFR on one flight can be operated IFR on another, implying that *"Autonomy"* is an operational state rather than an intrinsic attribute of a vehicle. An example of this is Garmin's Autonomí™ emergency automated landing technology. Autonomí™ is capable of operating autonomously in the IFR environment by leveraging 14 CFR 91.3 which states *"in an in-flight emergency requiring immediate action, the pilot in command may deviate from any rule […] to meet that emergency."* By declaring an emergency, Autonomí™ does not have to comply with ATC instructions, and it has the right-of-way over all other traffic. This reduces the number of constraints it must consider and therefore enables it to operate autonomously in the "emergency" IFR environment.

In the event that an aircraft is operated without a human crew, henceforth referred to as "crewless" or "uncrewed," the vehicle must be able to accomplish system-level functions on its own. For example, the vehicle must be capable of lowering the landing gear and flaps, as well as modulating its engine thrust. These functions must be accessible to an on-board computerized decision-making system to execute a trajectory. However, in the case of an Optionally Piloted Vehicle (OPV), those systems may also be manually operated by a crew. Again, Autonomí™ fits this description; in the event that a pilot is incapacitated, the system is capable of taking control of the aircraft systems to land the aircraft. In this context, *"Autonomy"* can again be considered as a state, which in this case depends on *how* system functions are executed rather than being an intrinsic attribute of the system.

In this document, *"Autonomy"* is defined as a state by two nested terms: *Functional Autonomy* and *Operational Autonomy*.

Functional Autonomy is a state whereby an on-board system has enough automation to perform system-specific tasks without external command and supervision. (e.g., an advanced autopilot following a four dimensional trajectory [xyz + speed] from a Flight Management System (FMS)).

Operational Autonomy is a state whereby a vehicle has enough on-board functional autonomy to achieve mission goals through autonomous *decision-making*, considering evolving external constraints, such as traffic, terrain, obstacles, weather, and airspace, without external command and supervision. For aircraft to be operationally autonomous, they must be capable of autonomous decision-making under all foreseeable normal and contingency conditions. Notably, this definition does not exclude crewed flight.

Supporting Concepts

In the Federal Aviation Administration's (FAA) Pilot Handbook of Aeronautical Knowledge (PHAK), decision-making (DM) is described as a process whereby through awareness of a situation, pilots take appropriate action at the occurrence or lack thereof of particular events. Situational Awareness is therefore a prerequisite for DM and is defined as "the accurate perception and understanding of all the factors and conditions within the five fundamental risk elements (flight, pilot, aircraft, environment, and type of operation that comprise any given aviation situation) that affect safety before, during, and after the flight".

For uncrewed aircraft, it will be shown that autonomous decision-making must invoke the following concepts: Digital Situational Awareness (D-SA), Digital Flight Visibility (DFV), and Vehicle Capabilities Assessment.

Digital Situational Awareness (D-SA)

Digital Situational Awareness (D-SA) comprises the system's knowledge of its own internal state (e.g., system health), as well as of external factors, such as weather, terrain, obstacles, traffic, and airspace and infrastructure. Through D-SA functions, the aircraft establishes an understanding of what a particular combination of environmental and system factors means with respect to successful mission completion. An aircraft flying in icing conditions must "know" that icing degrades aircraft performance and safety, and must therefore have the ability to respond appropriately to that particular event. Appropriate responses could include activating the ice-protection system, or diverting. To correctly perceive the icing conditions, the vehicle must have the capability to "see" its surroundings and select an appropriate action; in addition, the vehicle must "know" its own capabilities. Digital Situational Awareness is discussed further in Appendix A.

Digital Flight Visibility (DFV)

Classical flight visibility is an essential aspect of SA, and it is usually the defining factor for which operations may be conducted in a particular class of airspace. For flight under VFR, 14 CFR 91.155 explicitly specifies Visual Meteorological Conditions (VMC) requirements in terms of flight visibility and cloud clearance. VFR operations may be conducted as long as VMC prevails, and airspace and equipage requirements are met. Then, the ability of aircraft to navigate VFR is entirely predicated on the pilot's determination of the flight visibility in statute miles and cloud separation measured in feet. IFR requirements replace visual acuity by instrument performance, ATC control, and adherence to published procedures.

In IFR, a pilot's ability to navigate depends on how precisely the pilot/aircraft system can determine the aircraft's position. By relying on ATC for traffic deconfliction and published procedures for terrain and obstacle clearance, IFR pilots are able to navigate a highly structured air system with a sufficient level of SA while having a visual visibility below VFR minimums. IFR visibility is predicated on pilots replacing physical sight with ATC oversight for traffic deconfliction, and procedures for terrain and obstacle clearance. By combining ATC RADAR services with prescribed routings, altitude minimums and instrument procedures, aircraft crews gain *"instrument visibility,"* which can be characterized by the Actual Navigation Performance (ANP) achieved using the available navigation systems.

DFV is similar to Required Navigational Performance (RNP) which defines the precision, reliability, and availability requirements for a navigation system to fly in specified airspace or on particular routes or approaches. RNP therefore defines a performance-based standard for the entire suite of on-board sensors and databases that supply the navigation function; it does not mandate any individual piece of equipment, such as an Inertial Navigation System (INS). Similarly, DFV specifies the minimum system performance standards for the combined sensors, databases, and datalinks that supply the digital "visibility" function. DFV does not focus on a single sensor, such as the human eyeball, to specify the flight visibility.

In DFR, aircraft operations will not depend on ATC clearances and prescribed routings. Aircraft will be capable of maintaining separation from other aircraft independently, while maintaining terrain and obstacle clearance at all times. As in IFR and VFR, DFR aircraft will also have to maintain weather awareness and be capable of navigating safely within these constraints. During DFR operations, “visibility” has little to do with human optical acuity (particularly for uncrewed aircraft), and digital SA is predicated on the completeness of the data describing the environment in which aircraft operate autonomously.

Digital Flight Visibility (DFV) then, is the average time (or distance) horizon from the aircraft’s present location, that a system in DFR operations can detect terrain, traffic, weather, and obstacles based on a combination of static (database), on-board real time (sensor) and external (data-link) data.

There is a precedent to DFV in *Enhanced Flight Visibility*, defined in 14 CFR § 1.1 as:

> The average forward horizontal distance, from the cockpit of an aircraft in flight, at which prominent topographical objects may be clearly distinguished and identified by day or night by a pilot using an enhanced flight vision system.

This re-definition of visibility was required in order to obtain operational credit for the use of infra-red systems during low visibility approach operations. Exactly the same approach is proposed for DFR operations, where flight visibility is replaced by a suitably-defined DFV.

RNP can be considered analogous to DFV, in that it is a performance-based evaluation of how precisely and confidently navigation sensors (e.g., Inertial Navigation System (INS), Global Positioning System (GPS), Very-High Frequency Omni-directional Range (VOR), Distance Measuring Equipment (DME)) can determine aircraft location. DFV is also a performance-based evaluation of the accuracy, extent, completeness of the data describing the external environment (e.g., airspace, traffic, obstacles, terrain, airspace & infrastructure).

Examples of data sources that provide electronic SA include:

- Static terrain databases;
- Automatic Dependent Surveillance (ADS)-Broadcast and ADS-Contract and Very-High Frequency (VDL) datalinks;
- Flight Information System (FIS) and Traffic Information Services (TIS) Broadcasts;
- Terrain Collision Avoidance System (TCAS);
- Mode-S transponders; and
- RADAR and LiDAR.

The accuracy, timeliness, completeness, and availability of these data sources all contribute to the effective time horizon that the system can “see.” “Unrestricted DFV” implies the system has access to timely, accurate, and complete data to make a fully-informed decision regarding its trajectory. “Restricted visibility” is a function of the amount of data uncertainty (e.g., how old is the icing forecast? Is the traffic conflict ahead broadcasting intent data? How granular is the terrain database? …). The DFV concept, properly implemented, will provide the necessary sensory system Minimum Operational Performance Standards (MOPS) and Minimum Aviation System Performance Standards (MASPS) for autonomous DFR operations.

The following examples show how individual sensor performance contributes to and limits DFV, and how this metric differs from simple visual acuity:

1. Infrared Sensor:
   1.1. Thermal crossover: when the thermal signatures of two objects are indistinguishable, the system is "blind" to the presence of two distinct objects. For example, concrete runways can blend into the surrounding grass on infra-red displays, as the temperatures of the two media "cross-over" twice per day.
   1.2. Thermal imprinting: If a sufficiently hot body stays in the same place for long enough, residual heat on the surrounding objects or surfaces may trick a system into thinking something is there, when there really isn't. An example would be an aircraft that is held at the takeoff point before departure, which can imprint its thermal signature on the runway beneath it that persists after the aircraft departs.
   1.3. Blind to water: wavelengths do not easily pass through water, which means infrared sensors cannot see through clouds.
   1.4. Singe-frequency systems can be blind to the normal blue color of taxiway edge-lighting.
2. Doppler RADAR for turbulence detection:
   2.1. Blind to tangential velocities.
   2.2. Cannot detect turbulence without the presence of liquid water, so is blind to Clear Air Turbulence (CAT).

These examples show how systems that far exceed human visual acuity under some circumstances can be "blind" or suffer from "illusions" in other conditions which are not problematic for humans.

Vehicle Capabilities, Capability Margins and Available Power Profile (APP)

An autonomous vehicle must make decisions in-flight and on the ground based on the relationship between its capabilities and the demands of its environment. As a simple example, a vehicle without known-icing certification must avoid areas of known or forecast icing. Similarly, a vehicle with reduced DFV, as described above, may be limited in the type of operations it can conduct.

Vehicle Capability is defined as the system's performance capacity to respond to the environment in which it operates, measured numerically by performance metrics or descriptors.

Examples:

1. Powerplant
   1.1. Energy capability: to add, subtract or maintain potential and kinetic energy, described by the powerplant's power profile
      1.1.1. Numerical: 1000 horsepower
      1.1.2. Performance: Rate-Of-Climb (ROC), acceleration, range
   1.2. Hover capability:

        - 1.2.1. Performance: time
2. Flight Control System:
    - 2.1. Maneuvering capability:
        - 2.1.1. Descriptors: multiple rotors
        - 2.1.2. Performance: pitch rate, bank rate
    - 2.2. Crosswind capability:
        - 2.2.1. Performance: wind magnitude
3. Ice protection:
    - 3.1. Flight into icing capability:
        - 3.1.1. Descriptor: icing intensity
        - 3.1.2. Numerical: gallons of anti-ice fluid
        - 3.1.3. Performance: time in icing
4. Aircraft Structure:
    - 4.1. Turbulence capability:
        - 4.1.1. Descriptor: turbulence intensity
        - 4.1.2. Performance: airspeed
5. Navigation System:
    - 5.1. Precision capability:
        - 5.1.1. Performance: Actual Navigation Performance (ANP)

Vehicle Capability Margin: A comparison of available system capability with capability requirements demanded by the context in which the capabilities are being evaluated.

*Example*s:

i. Performance Based Navigation (PBN) Required Navigation Performance (RNP) specifications detail required positional precision in nautical miles depending on where the aircraft is operating. Actual Navigation Performance (ANP) is the positional precision achieved by the pilot/vehicle system in real-time. In this example, the navigation system's precision capability margin is the difference between the RNP and the ANP. A positive value indicates the vehicle's positional capability is sufficient for the current flight phase, whereas a negative value indicates that the vehicle cannot achieve the required navigational performance level.

ii. Flight into icing conditions requires the ice protection system be capable of protecting the airframe from ice accumulation for the entire duration of the icing conditions. For an aircraft with weeping wings, the capability margin is driven by the amount of available fluid and the ice accretion rate. The margin can be expressed in minutes or miles of remaining range.

The advent of electric vehicles adds a new element that has not been contemplated by the current regulations: the maximum available electrical power is not constant, but declines as the flight progresses. This is quite different from a conventional fuel-powered aircraft, where maximum power and performance are available until the fuel is exhausted. This has important ramifications. For example, a sub-optimum routing could reduce the power reserves to a point where a transition to hovering flight (which is the limiting power case for most Electric Vertical Takeoff and Landing (eVTOL) aircraft) cannot be achieved. This introduces the concept of ***Available Power Profile (APP)***, which encompasses the maximum three-dimensional capability (e.g., altitude, airspeed, endurance) of the vehicle. In this example, the APP defines if a successful transition to a hover can be accomplished with adequate reserves. The APP must be continuously computed by the vehicle for its own trajectory definition purposes, and it must also be communicated as part of the intent data to third-parties to ensure that any cooperative decision-making (such as strategic trajectory deconfliction) does not encroach on the required minimum capability margins. This concept is useful for traditionally powered vehicles, but essential for eVTOL aircraft. APP is analogous to the Lowest Acceptable Altitude (LAA) used for some military jet operations to ensure adequate destination fuel reserves.

Available Power Profile: A subset of Capability Margin, the Available Power Profile defines how the remaining energy can be allocated. This is an important concept for electric vehicles, since the instantaneous and future available power depend on at least the present and past rates of discharge and battery temperature. Consider the following examples:

1. An electric vehicle is in icing conditions and must activate its ice protection system. To do so, it allocates enough battery power to keep critical surfaces clear of ice. This accelerates the battery depletion and lowers the maximum power output, which in turn impacts cruising speed, maximum hover time, or the ability to hover outright.
2. An electric vehicle receives an instruction to enter a holding pattern with an Expect Further Clearance time 20 minutes in the future. Before accepting the instruction to hold for 20 minutes, the vehicle evaluates its powerplant capabilities and available margins by analyzing its power profile to determine if the instruction is achievable. For instance, if the vehicle can only hold for 15 minutes before running out of energy reserves over the remaining flight trajectory, then it has a negative holding capability margin and cannot comply. Similarly, acceptance of the holding clearance could reduce the available hover time at destination.

Capability Margins (including APP) should be used by the vehicle automation or the external controlling entity to negotiate a clearance that could be acted upon, while preserving the necessary performance margin for safety. This might entail a back-and-forth negotiation between the vehicle and the controlling entity or the outright refusal of the “clearance.” The concept of Capability Margin provides the automation with the awareness of what is achievable, by how much, and what is not.

Functions Analysis

This section presents functions that must be performed to operate autonomously in a DFR environment. The functions can be executed by a machine, a human, or in some combination, to allow a vehicle to operate autonomously in the future DFR environment.

The process for defining the airborne autonomous decision-making functions begins with the standard references for any complex aircraft system development program: The Society of Automotive Engineers (SAE) Aerospace Recommended Practice (ARP) 4754 *Guidelines for*

Development of Civil Aircraft and Systems (1996). This Aerospace Recommended Practice defines a set of high-level system functions which are used as the basis for the subsequent analysis [2]. As the document was not intended to address unpiloted vehicles and Simplified Vehicle Operations (SVO), a number of functions have been added to address these operations. Conversely, some aspects of ARP-4754 are less relevant for the autonomous decision-making task, such as cargo handling, and these functions are not addressed in this functional analysis. They could be incorporated for operations where the cargo handling is an integral part of the decision-making process.

The following analysis uses a top-down approach, starting with the major ARP-4754 top-level functions, and decomposing these into their constituent decision-making components. Specific examples are listed for many of these functions for illustrative purposes only, and the examples themselves should not be treated as comprehensive. The analysis is focused on airborne decision-making, and does not address routine vehicle functions, such as extending the landing gear before landing. These routine functions are grouped under a broad "Systems Management" function.

Top-level Automation Objective

For the purposes of this analysis, the fundamental objective of an autonomous aircraft decision-making system (DMS) is to define and execute a trajectory that meets the mission objectives, subject to constraints, and responding to conflicts and immediate imperatives. Certain portions of the trajectory may be optimized, but the focus of the DMS is to first and foremost comply with trajectory constraints and resolve conflicts, which are defined below. This top-level function is referenced as *Trajectory Management* for the remainder of the analysis.

Integral to the achievement of the Trajectory Management objective, the DMS must also integrate a number of support functions, including systems health monitoring, communications, systems management, etc.

Functional Categories

The following top-level categories are used to classify different aspects of decision making. There are numerous ways to classify functional categories. The following are used throughout this report, and they differ slightly from the prior work of Wing et al. [53] There is some inevitable overlap between these classifications, but they form a useful organizing framework:

1. Mission Management: comprises strategic decision-making for the attainment of the mission objectives subject to applicable mission constraints (e.g., minimum time and cost, ETOPS, Reduced Vertical Separation Minima (RVSM) operations). Mission management functions maintain and revise the objectives and parameters of the mission, which ultimately define the overall flight trajectory, but do not generate control inputs to the vehicle. The mission constraints bound the trajectory optimization.

2. Trajectory Management:

   Trajectory management addresses both the overall flight path management and near term tactical operations:

    2.1. *Flightpath Management*: decisions triggered by strategic constraints or tactical conflicts with a near-term impact on the flight trajectory which are likely to result in near-term control inputs to the vehicle. A number of optimized trajectory options may be available, but they will likely be limited in scope and number. Failure to comply with a trajectory constraint may result in a conflict or an immediate imperative requiring an escape response.

    2.2. *Tactical Operations*: decisions requiring either a prompt response with limited optimization effort, or immediate control inputs typically with only one offered "escape" trajectory (e.g., TCAS Resolution Advisory (RA), Enhanced Ground Proximity Warning System (EGPWS) warning). Conflicts requiring an escape maneuver are generally not trajectory optimized. Failure to respond correctly in a timely fashion may result in an undesirable outcome.

3. Vehicle Management:

    3.1. *Vehicle Control*: functions that stabilize the vehicle and execute the control and guidance functions to achieve the mission, flightpath, and trajectory objectives defined above.

    3.2. *Systems Operation*: functions that control the vehicle systems that support the execution of the trajectory.

Conflicts, Constraints & Trajectories

One of the primary functions of the DMS in the execution of the Trajectory Management function is to prioritize and comply with constraints and resolve conflicts. Both constraints and conflicts are defined by environmental factors or vehicle system factors. In many cases, these are inter-related through the concepts of Vehicle Capability and Capability Margins (Figure 1). Vehicle system factors also independently influence the trajectory and are closely linked to the systems management function.

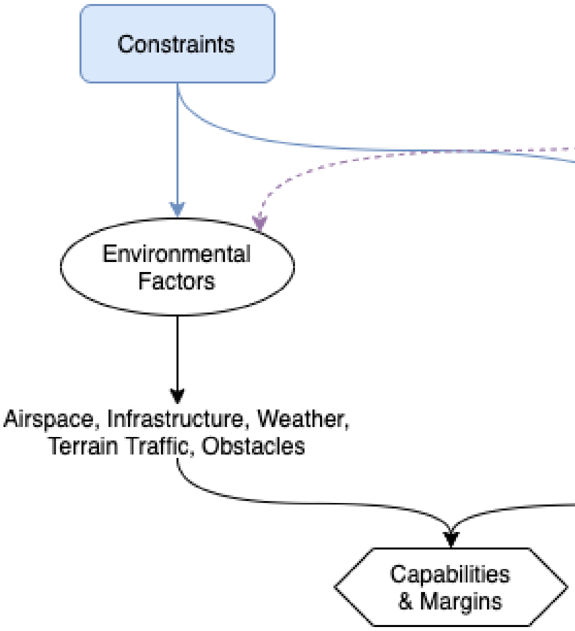

Figure 1: Constraints and Conflicts inter-relation

Constraint

A constraint is a boundary condition for the trajectory optimization function and does not require a "resolution."

Examples of constraints set by environmental factors are:

1. Required Time of Arrival (RTA) at the destination airport provides the trajectory optimization function with a desired trajectory end time.
2. Minimum Enroute Altitude (MEA) limits the altitudes the optimization function can consider.
3. Prohibited airspace define volumes of airspace the vehicle must avoid.

Examples of constraints set by vehicle system factors are:

1. The service ceiling bounds the altitudes that the optimization functions can consider. Combined with MEA's mentioned above, the optimization function is limited to a defined band of accessible altitudes.
2. The undercarriage configuration defines the types of landing surfaces that are accessible to the vehicle for a safe landing.
3. The powerplant constrains the maximum speed attainable and defines energy consumption rates which are factors the optimization function must consider.

Conflict

A conflict is generally an unplanned element that requires a "resolution" and is the product of incompatible environmental demands and available vehicle system capabilities. A resolution is either:

1. A new optimized trajectory that accomplishes the original mission objectives within the original mission constraints. The conflict is then considered a constraint of the new optimized trajectory (Figure 2).

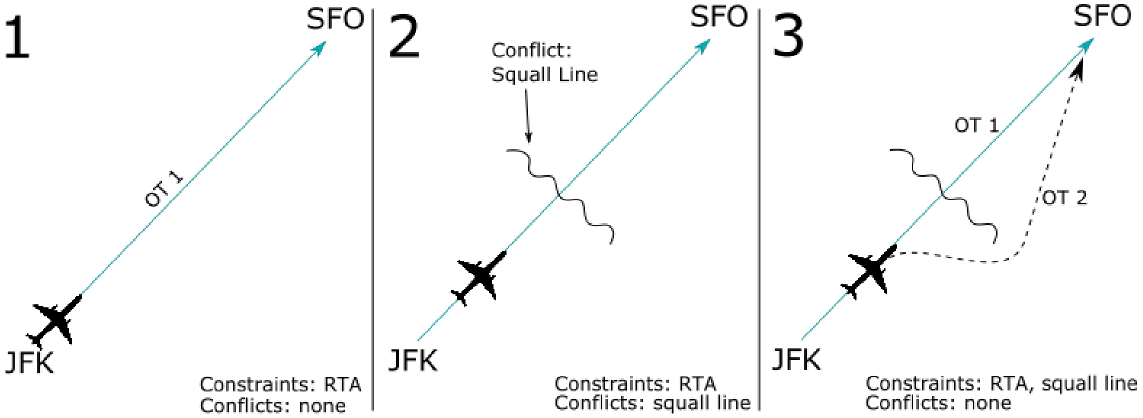

Figure 2: (1) Optimized Trajectory (OT) 1 is established between JFK and SFO. OT1 has one constraint (Required Time of Arrival, RTA) and no conflicts. (2) An unanticipated squall line is detected, requiring trajectory replanning. OT1 now has one conflict (squall line) and one constraint (RTA) (3) OT2 is calculated, and the original mission objectives can be maintained. OT2 has two constraints (RTA, squall line) and no conflicts.

2. A new optimized trajectory that no longer meets the original mission objectives and original mission constraints. The conflict triggers a re-assessment of the original mission objectives and constraints (Figure 3).

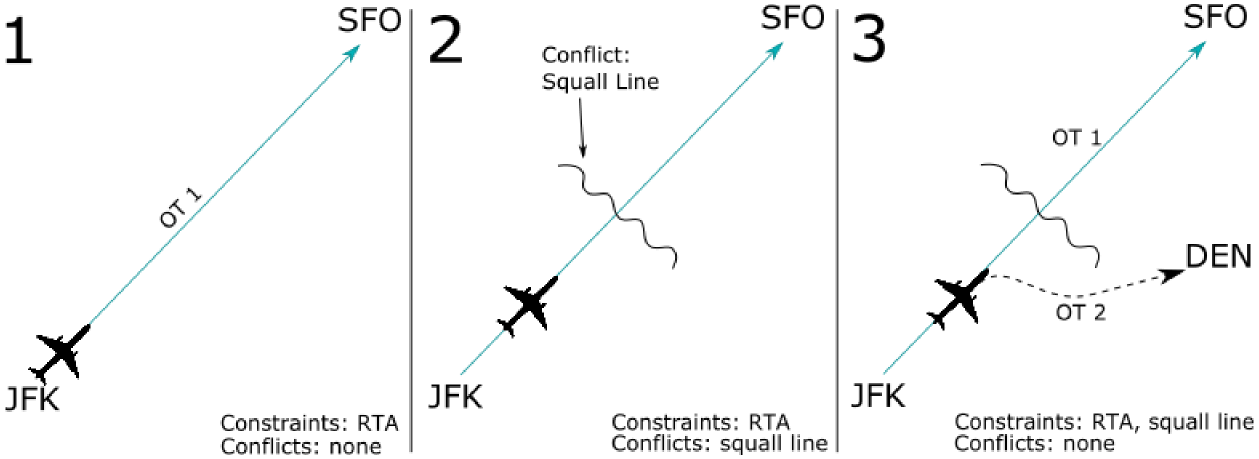

Figure 3: (1) Optimized Trajectory 1 (OT1) is established between JFK and SFO. OT1 has one constraint (RTA) and no conflicts. (2) An unanticipated squall line is detected, requiring trajectory replanning. OT1 now has one conflict (squall line) and one constraint (RTA) (3) OT2 is calculated, and it is determined that the original mission objectives cannot be maintained. OT2 has two constraints (RTA, squall line), no conflicts, and accomplishes a revised mission objective.

3. An immediate non-optimized escape maneuver, such as a TCAS-II or EGPWS resolution advisory.

Trajectory

A trajectory is an output of the DMS and is the result of comprehensive analysis of the effect of all constraints and conflicts on the mission objectives. Trajectories are always subject to change and are ultimately constructed as a series of points that are each traceable to constraints. Points are anchored in time and/or three dimensional (3D) position, and they can be event-driven. Event-driven points are considered "floating points" since they are not anchored in time or position, but rely on environmental inputs to trigger a system response. Points are characterized by at least:

1. a change in speed, heading or altitude,
2. a systems management action, or
3. a combination of 1 and 2.

In addition, trajectories are subdivided into segments characterized by goals. For example, a vehicle flying from John F Kennedy (JFK) to San Francisco (SFO) may divide its trajectory into three distinct segments:

1. Departure segment goal: reach a fix anchored in time and 3D position with flaps and gear up.
2. Cruise segment goal: fly an energy optimal trajectory to an event driven fix defined by the reception of an approach clearance by ATC.
3. Approach segment goal: land the aircraft within the first 5000 ft of available runway.

Figure 4 represents a sample trajectory based on the three segments defined above. This trajectory is included as an example only and does not define "trajectory." It is conceivable that trajectories might include many more segments defined by many more goals.

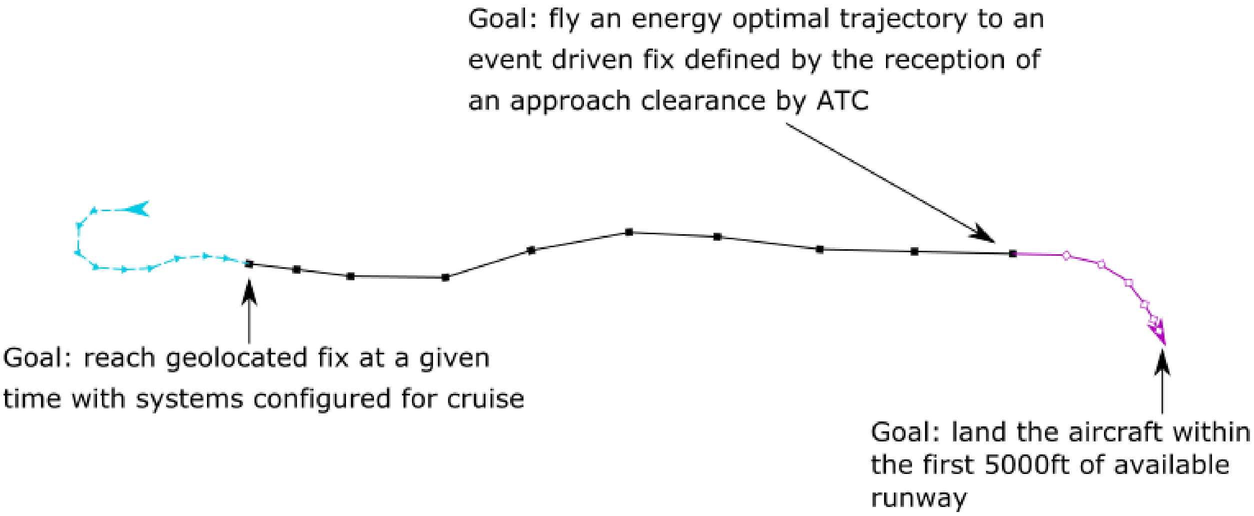

Figure 4: Sample trajectory divided into three segments. The departure segment is shown in blue with triangular markers. The cruise segment is black with square markers, and the approach segment purple with hollow square markers. Each segment ends at a terminating fix, at which point a goal is achieved.

Decision Making System Overview

The DMS is the agent that processes and prioritizes objectives, constraints, and immediate imperatives to produce and maintain an optimized vehicle trajectory that accomplishes the mission goals. The process is hierarchical, beginning with data collection, through data interpretation, and onto trajectory definition and execution. For a piloted vehicle, the pilot could execute some or all of the DMS functions. For a fully autonomous uncrewed vehicle, the DMS would reside in hardware and software.

A high-level cyclic representation of the DMS decision-making flow is shown in Figure 5.

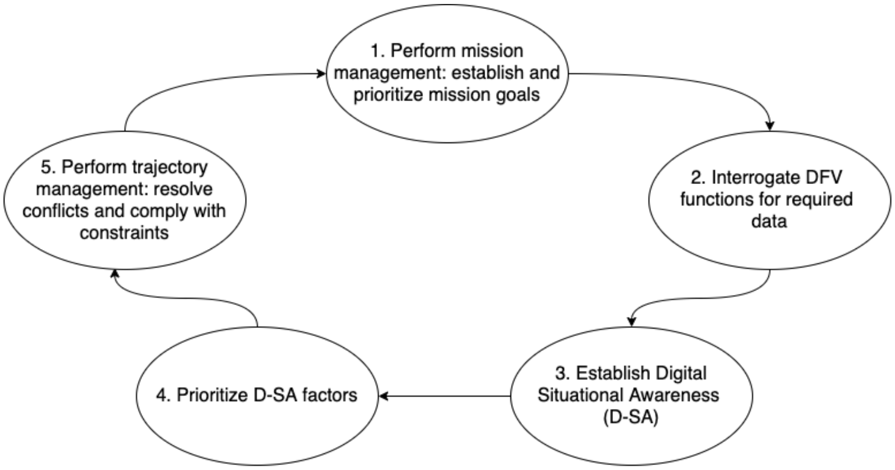

Figure 5: DMS decision-making flow

D-SA Factor Prioritization

As part of the decision-making process, the DMS prioritizes the D-SA factors from all available sources, including, but not limited to:

- Mission Objectives (e.g., cost, time, or energy optimization)
- Vehicle state and performance margins
- Pilot health state
- Immediate imperatives
- Terrain/Obstacles
- Weather (capability & energy margin)
- Airspace & Infrastructure (e.g., preferred routes, airspace user fees, ETOPS, Special Use Airspace (SUA))
- Traffic

Although the preceding list is not intended to convey any specific prioritization, it will be necessary to encode such prioritizations in any decision making scheme so that conflict resolution and trajectory optimizations can be performed based on the relative importance of each prioritized data element.

The DMS is composed of the following function modules:

1. Mission Management;
2. Trajectory Management;
3. Digital Situational Awareness;
4. Digital Flight Visibility; and
5. DMS Support

Mission Management Function

This DMS function relates to the evaluation and monitoring of the optimized trajectory[1] to accomplish mission objectives. This function is addressed in Appendix B: DMS Mission Management Functions.

Trajectory Management Function

In flight, the trajectory management DMS function generates candidate vehicle trajectories according to conflicts and constraints communicated by the appropriate D-SA functions. It then selects the optimum vehicle trajectory from the available candidates as the one that maximizes the attainment of the mission goals (e.g., minimum energy expenditure) while meeting all identified constraints.

The trajectory management functions relay the optimized trajectory to an external entity to the DMS that is responsible for the execution of the optimized trajectory, such as an FMS and autopilot. Reactive systems such as TCAS-II and EGPWS may short-circuit the DMS to comply with immediate tactical imperatives. Current TCAS and EGPWS implementations do not exercise vehicle control, but this function must be implemented for a fully autonomous vehicle. Trajectory Management functions are listed in Appendix C: Trajectory Management Functions.

Digital Situational Awareness (D-SA) Function

D-SA functions are at the heart of the DMS. Each function-flow is responsible for a specific D-SA task, such as terrain awareness. The D-SA functions use data from the DFV and support functions to identify and define constraints, conflicts, and possibly candidate trajectories which are relayed to the Trajectory Management function. The D-SA functions can be integral to the DMS or executed by stand-alone systems such as TCAS and EGPWS, which are capable of commanding trajectory changes autonomously. Current TCAS and EGPWS systems can initiate Resolution Advisories (RA) and Terrain warnings respectively, but these are not generally interfaced to the aircraft's flight control system. In contrast, fully autonomous vehicles' flight control systems must be able to act upon these RAs and warnings. D-SA functions are listed in Appendix D: Digital Situational Awareness (D-SA) Functions

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[1] SAE ARP4754 "Navigation" aircraft-level function

Digital Flight Visibility (DFV) Function

The following DMS functions address the digital flight visibility related to the autonomous vehicle functionality. These functions are pre-requisites for digital SA but are distinct because there is no decision making associated with them. The functions described are independent of standalone systems such as TCAS, Airborne Collision Avoidance System (ACAS) X, Ground Collision Avoidance System (GCAS), EGPWS, etc. which will override the DMS decision making process for escape maneuvers (c.f. DMS Decision-making Flow). DFV functions are listed in Appendix E: Digital Flight Visibility Functions.

DMS Support Functions

DMS support functions provide data to the D-SA and Trajectory Management functions, but the support functions do not output trajectory constraints or candidate flight paths. DMS support functions are categorized as follows:

1. Communication functions
2. Capability Margin Assessment functions
3. Vehicle Awareness functions

The complete function list can be found in Appendix F: DMS Support Functions.

The relationship between the DMS DFV, D-SA, Trajectory Management, Mission Management, and Support functions is shown in Figure 6.

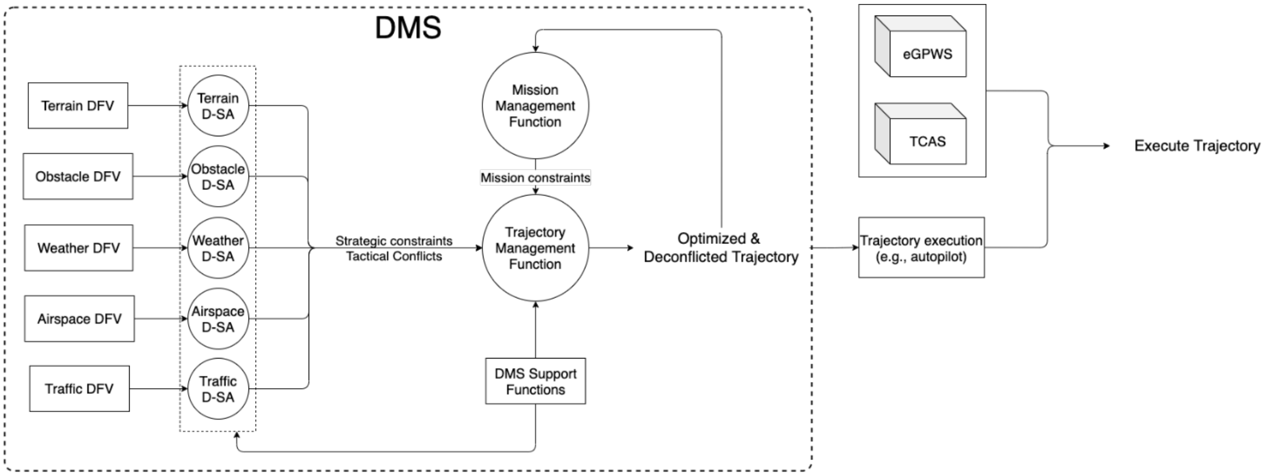


Figure 6: DMS function relationships

DMS Decision-making Flow

Mission Management continuously monitors the actual vehicle trajectory against the planned trajectory and sends mission constraints to Trajectory Management. In addition, Trajectory Management continuously interrogates the D-SA functions for updated D-SA data and conflicts and recomputes the optimized trajectory accordingly. The DMS process is shown in Figure 7.

The DMS process continuously loops throughout flight. If a conflict is detected by a D-SA function, the function executes a flow of ordered sub-functions and relays the conflict to Trajectory

Management. Trajectory Management assesses and prioritizes the known conflicts, and, assuming no escape maneuver or externally approved trajectory must be executed, assesses the mission constraints, and defines a new optimal route. If the mission level objectives can still be met, Trajectory Management re-checks for conflicts. If no new conflicts are detected, the new optimized trajectory is executed. If mission objectives can no longer be met (e.g., the new optimal route is too long, an optimal route could not be calculated within the constraints), the mission objectives are revised, and the entire loop is executed from the top. A sample DMS flow is listed below and illustrated in Figure 7.

1. Check for conflicts
    - 1.1. weather conflict relayed by Weather D-SA function 9.6.4: **Convective Cell**
2. Trajectory Management assesses and prioritizes known conflicts
    - 2.1. Analyzes conflict definition provided by function 9.6.4 (e.g., cell dimensions, location, observation time, valid forecast time, distance to ownship)
    - 2.2. Adds weather conflict to prioritized list of conflicts
3. Escape maneuver required?
    - 3.1. Decide an escape maneuver is <u>not</u> required in this case
4. Assess mission constraints
    - 4.1. Define the optimization bounding values (e.g., RTA, Minimum Enroute Altitude (MEA))
5. Define optimum trajectory
    - 5.1. Optimize trajectory to avoid the weather conflict
6. Able to meet mission objectives?
    - 6.1. Determine if new optimized trajectory is achievable by the vehicle by executing appropriate support functions (e.g., define available power profile, capabilities)
    - 6.2. In this example, the new trajectory does not require revised mission objectives
7. Check for conflicts
    - 7.1. No new conflicts have been detected
8. Execute trajectory
9. <u>Loop back to:</u> Assess mission constraints

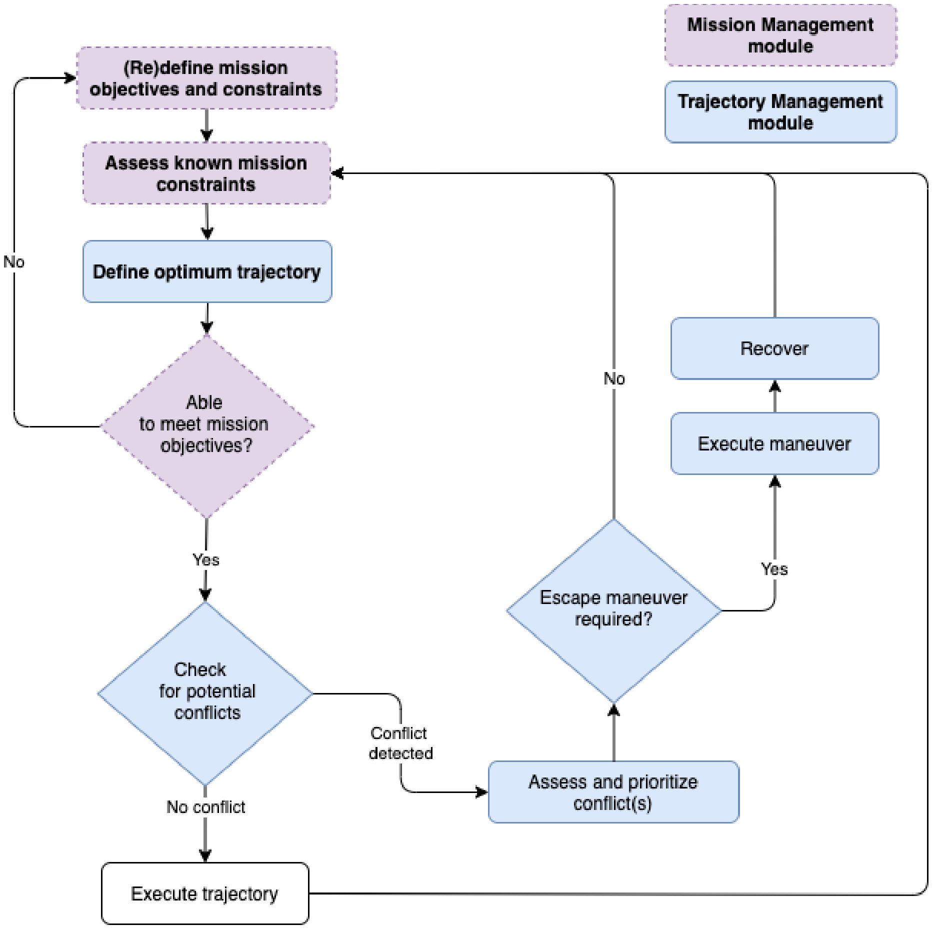


Figure 7: DMS process. Blue boxes are performed by Trajectory Management, and purple dashed boxes by Mission Management. "Execute trajectory" is performed by an autopilot – FMS combination, for example.

In the event an escape maneuver is required, the conflict is hoisted as an immediate imperative. Immediate imperatives may be executed externally from the DMS by technologies such as TCAS-II, ACAS-X, GCAS or EGPWS. Once the escape maneuver is complete, the DMS regains control at the level at which it was interrupted.

Functions Ontology

The complete functions list is composed of many different interconnected functions, the relationships of which can seem convoluted when viewed in bullet form. Additionally, the functions are used to define incremental implementation paths, described in Section 2. To properly grasp the inter-dependencies between the functions, they are programmed into an ontology which exposes explicit and implicitly inferred relationships between them. This facilitates the building of the paths to autonomy, since the ontology eliminates the need to explicitly define every step in the path. By virtue of its relational properties, the ontology automatically invokes every element within each path building block. Further, the ontology can help reveal hidden dependencies that might not have been explicitly stated during the path construction. The ontology is discussed in detail in Appendix J: Functions Ontology.

Section 2: Paths to Autonomy

Introduction

To implement the functions described in Section 1: Functions for Autonomy, “paths to autonomy” must be defined. Presently, regulations do not allow for AAM operations such as UAM because they require, for example, novel technologies and flight rules for which there is no existing regulatory framework. This means that as long as supporting regulations do not exist, new technologies such as electric propulsion cannot be deployed. Conversely, as long as technologies do not have the opportunity to prove themselves, they are unlikely to ever be approved by the regulator, leading the industry to a chicken-and-egg conundrum.

Paths to autonomy resolve the current chicken-and-egg situation by identifying how to leverage existing regulations to allow for the implementation of novel functions and technologies in small, incremental steps. For each path, as individual steps are overcome, more functions and technologies will have had the opportunity to be tested, and data about their performance gathered. The data gathered along a path to autonomy is then used to inform the regulator what laws should be written and how, and will inform the designers how to better their systems. At a minimum, paths to autonomy must consider existing regulations and airspace, the aircraft functions which are to be implemented, and the latest technological developments. The analysis of these factors is contextualized by a use case for which there is a viable business case.

The following discussion on “paths” approaches autonomy according to the definition provided in Section 1; the distinction between functional and operational autonomy is preserved to dissociate “aircraft airworthiness” certification and “operational” certification. This way, the issue of implementing autonomy is approached from two converging perspectives. In the first case, contemporary *crewed operationally autonomous* vehicles will operate under DFR, with present day certified technologies; in the second case, novel *uncrewed* (i.e., functionally-autonomous) aircraft will operate under DFR in the same airspace. Both types of aircraft must have operational autonomy to conduct DFR operations, but achieve it differently: one through comprehensive automation, and one with a traditional pilot providing the majority of the decision-making.

This two-pronged approach effectively dissociates the technological challenges associated with crewless aircraft from the implementation challenges associated with operating autonomously. While the “crewed operational autonomy” approach is used to inform future operational rules and certification requirements for future DFR operations, the “uncrewed functional autonomy” approach is used to define the incremental steps needed to attain complete functional autonomy. The final objective is for both approaches to converge, enabling the functionally autonomous vehicles to operate autonomously under DFR in a certification regime that allows this.

This section describes a method based on first-principles reasoning to define paths to vehicle autonomy, and it concludes with four distinct examples demonstrating the application of the method. The emphasis is on the structured method, rather than the paths themselves. The method builds on the functions derived in Section 1, and it is consistent with the definitions and concepts discussed therein. The sample paths are not intended to be "the" definitive paths to autonomy; rather they serve to demonstrate the application of the method. The following sections are organized as follows:

1. Methodology Summary provides a high-level description of the method and assumptions.
2. Methodology Discussion presents an in-depth analysis of each step in the method. Important points of consideration such as airspace, functional allocation and the technological state of the art are discussed generically.
3. Paths Analysis applies the method to four different use cases and draws upon the discussions of the previous section to build four specific incremental paths to vehicle autonomy.

Methodology Summary

Four Step Process

Step 1 - Use Case Identification. The analysis begins by identifying a commercially viable business case to generate a use case which drives the path. With few exceptions, a use case without a supporting business case (i.e., an anticipated profitable outcome) has little chance of success, because the path must address numerous regulatory and societal hurdles which may be harder to solve than the technical difficulties required to accomplish the automation. Accordingly, the identification of market drivers that motivate the adoption of full autonomy is vital to the path development process. Uber's 2016 white paper on Urban Air Mobility identified a business case for inter-urban passenger air transportation, and it argued that the infrastructure and operations costs of such a system would compete with those of building, maintaining, and operating existing "roads, rails, bridges and tunnels" [33]. Uber defined use cases in San Francisco, São Paulo, and New Delhi to study the feasibility of the business case. The definition of use cases provides the analysis with a context to ask relevant questions such as: what is the mission, where are the flights taking place, what is the airspace, and what are the vehicle design requirements? The use case does not constrain the analysis to a subset of functions. On the contrary, it is intended to ensure that none of the requisite functions have been accidentally omitted. In UAM for example, the location of the mission imposes stringent noise requirements that must be met for public acceptance. This requirement has a profound impact on the vehicle design, which could limit the vehicle size and range. The sample paths outlined in this report follow a similar thought process to highlight how specific functions are entrained into the path.

Step 2 – Regulations and Airspace Analysis. This step identifies regulatory and airspace realities that define the current certification and operating environments, with a focus on operational regulations (e.g., 14 CFR § 91 and § 135). Major regulatory impediments to implementation are identified and used as a basis to identify path initial conditions. For instance, it is reasonable to adopt a constraint that current airspace structures and procedures will not change drastically in the short-term, or that airports will not be built or modified overnight. It is highly desirable to find ways of implementing autonomy that minimize the required changes to existing regulations and procedures, while adopting a very gradual and measured pace of regulatory reform. This requires a proactive and parallel approach to instituting regulatory changes, as will be discussed in the certification section.

While the automation-path start-points are anchored in procedures that have already been accepted by the flying public and the regulator, they inevitably raise questions that challenge the status quo. For example: why can't crewed aircraft be operationally autonomous when operating in Instrument Meteorological Conditions (IMC) without being on an IFR flight plan? Why can't functionally autonomous systems, such as Garmin Autoland, be used in normal (i.e., non-emergency) operations? While the implementation paths' initial conditions must push existing boundaries, they are also shaped by these rigid realities that must be respected in the short term. This aspect is often missing from some of the more aggressive autonomy visions, yet the ability to walk before running is a well-proven maxim that should be respected.

The regulatory assessment, to be conducted in conjunction with the FAA, will also identify the data that must be collected using functionally autonomous (crewed for safety) vehicles to establish the demonstrated Design Assurance Levels (DAL) that will be credited towards the requirements for true operational autonomy.

Step 3 – Functions Layering. This step leverages the outcomes of Steps 1 and 2 to contextualize the functions presented in Section 1: Functions for Autonomy. A governing assumption of the function generation task was that **there exists a core set of required aircraft functionality for *all* use cases and types of crewing combinations, namely SPO, SVO, remote pilot, and no pilot**. Depending on the mission and the environment in which is it carried out, functions can be allocated to the machine, the human, or a combination of the two. Functions that are specific to the use case and the environment may also be identified at this stage. For example, a function to detect static obstacles (e.g., buildings) will likely be more critical for electric UAM vehicles than for single pilot airliners.

The functional allocation will be based upon the time-tested incremental approach, where the initial functional allocation to the automation is limited in scope, complexity, and vehicle integration. Examples include advisory systems such as trajectory managers, which offer candidate solutions to the pilot who is the ultimate arbiter. This approach has many precedents, including contemporary FMS which are capable of inserting dozens of waypoints and entire approach procedures using a few keystrokes. The human pilot is expected to fully verify the resulting waypoints against independent sources, such as en route and terminal charts. Sufficient confidence has now been obtained with these procedures that the need for carrying paper charts has been eliminated for all IFR operations for suitably-equipped aircraft and properly trained crews. Similar progress has been made with the transmission of simple ATC instructions and clearances using datalink services such as VDL and ACARS.

As confidence is gained on the advisory automated functions, these can be expanded and deepened. Once again, there is ample precedent: aircraft have been certified for automatic landings since the 1960s, and the technology for fully automating the control of the vehicle is already mature. The required increment would integrate the advisory functions provided by trajectory managers and FMS performance modules with the high-authority digital flight control systems that are already well validated. This would, once again, be performed with human pilot supervision, until sufficient confidence is gained in the new level of automation authority and integration. As a further increment, certain existing standalone systems such as EGPWS, windshear alerting systems, and TCAS resolution advisories would be integrated into the flight control systems. (Military automatic Ground Collision Avoidance Systems – GCAS – *do* interface with the flight controls, because they specifically address g-induced pilot loss of consciousness. Current civilian EGPWS systems do not control the aircraft flightpath directly.) As a further step, the increasing levels of automation would be applied to the system-level functions of the aircraft, to allow strategic in-flight planning decisions to be executed. This process would culminate in a full allocation of all flight functions to the automation, including aircraft emergencies such as engine failures and other system emergencies.

While each incremental assignment to the automation is being undertaken in the piloted environment, suitable data will be collected to establish the confidence required at each step. This will allow the development of a suitable incremental regulatory response to the increasing level automation, whereupon the new function can be transitioned to the crewless scenarios. The latter would initially be conducted over sparsely populated areas, in segregated airspace, and for overwater flights to reduce the risk profile. Eventually, sufficient confidence will be achieved for the unrestricted operational implementation of each particular level of automation. This is exactly analogous to the Extended-Range Twin Operations (ETOPS) rollout for twin-engine air carrier aircraft. Initially, such operations were limited to 60 minutes flight time from a suitable landing alternate in the event of a failure of an engine. The time limit was raised incrementally to 240 minutes and beyond, which effectively allows unrestricted worldwide overwater operations for suitably certified aircraft.

The outcome of this step is a therefore a logical, incremental layering of functions and their allocation between the human and the automation, with a parallel maturation of the airworthiness and operational certification regulations, supported by a growing body of supporting design assurance evidence.

Step 4 – Technologies Analysis. Based on Step 3's tailored functional allocation between the pilot and the automation, Step 4 analyzes the technology requirements that enable the selected use cases. Although the technology analysis is presented here after the functional breakdown, Steps 3 and 4 may have significant overlap.

Creativity is the key here. Wherever possible, examples of existing technologies, research work, or scenarios where technologies *could* be applied are provided. Specific companies and systems are identified in the path analysis that follows because their technologies serve to demonstrate key points in the analysis; the intent is not to endorse individual offerings but rather to highlight the potential that they unlock for the entire industry. The technology analysis may be used to define a preliminary timeline for implementation, and it is informed by regulatory change requirements and the progress made by industry committees such as ASTM and RTCA. For example, ADS-B Out, which is an enabling technology for traffic D-SA functions, became mandatory in the United States in January 2020. Similarly, ACAS-Xu, a technology that resolves traffic Resolution Advisories in 3D, will be critical for the implementation of UAM in dense airspace. In December 2020, RTCA published DO-386 Minimum Operational Performance Standards (MOPS) for ACAS-Xu. Implementation of technologies and publication of consensus standards may or may not be specified at specific points in time; the key takeaway is that they help guide the order in which path steps are specified.

The following sections provide points of discussion for each step. Because they are highly inter-related, steps may overlap in the discussion because a point made in one step may provide the required background for the presentation of a technology, a function, or an airspace concept. However, the final output of these discussions are four proposed stepped paths that push autonomy forward.

Principles and Assumptions

In generating the paths to autonomy, a number of principles and assumptions are proposed. The fundamental premise that underlies all of the paths is that a solid identified market exists with a profitable outcome. Otherwise, it is highly unlikely that a path could be driven to its conclusion, notwithstanding the technical capability to do so. Other important guiding principles and assumptions are:

1. **What already works shall be preserved**. Disruption to present day IFR and VFR operations should be minimized as much as possible. To IFR and VFR crews, DFR aircraft should not require special treatment or different procedures, minimizing the potential for additional pilot training or new equipage requirements. DFR aircraft should seamlessly integrate in the existing airspace.
2. **Technological, regulatory, and societal-impact changes must be incremental**. This is a widely respected rule for flight test operations (alternatively called the “build up“ approach) which has been proven to minimize program and technical risk. This principle is particularly important for the emerging eVTOL/AAM market, where so many revolutionary changes are being proposed simultaneously on each of these fronts.
3. **A viable path must leverage existing policies and regulations while putting pressure on them to evolve in the desired direction.** Existing regulations provide opportunities to test novel technologies, functionalities and operations, the results of which should then be used to inform how to write new regulations. For example, decision-making systems will require many hours of data gathering to demonstrate their safety and reliability before they can be certified according to new regulations.
4. **New flight rules will be required to support autonomous operations**. VFR and IFR operations generally assume human pilots and define procedures that may be impractical for uncrewed aircraft . For example, right-of-way rules defined in 14 CFR 91.113 and IFR minima rules defined in 14 CFR 91.175 are specified as a function of “flight visibility”, defined by 14 CFR 1.1 as “the average forward horizontal distance, from the cockpit of an aircraft in flight, at which prominent unlighted objects may be seen”. To “see” may have to be formally defined, and new requirements will have to be rewritten to tailor for the absence of human crews.
5. **The Digital Flight Rules proposal is used to capture required changes to existing flight rules (IFR/VFR).** DFR implies the assignment of separation responsibility to the aircraft in all weather conditions, thus implying crews capable of taking on that responsibility shall

also be able to operate DFR. A redefinition of terms such "pilot in command" and "flight visibility" will be required, and new operational rules compatible with those definitions will have to be written.

6. **Digital Flight Rules must be compatible with Visual and Instrument Flight Rules**. To increase compatibility with the existing airspace infrastructure, procedures and neighboring aircraft, autonomous aircraft should be capable of supporting IFR-like and VFR-like operations, when required. For example, autonomous aircraft should still be capable of receiving and executing ATC instructions. This assumption also supports the requirement defined by the first assumption.
7. **Technology Readiness Levels (TRL) of systems to automate the mechanics of flight are either well advanced or will be.** Systems such as Airbus' Autonomous Taxi, Take-Off, and Landing (ATTOL) [46], coupled with advanced autopilots already capable of auto-land and of following complex 4D trajectories show that aircraft flight is to a large degree capable of being automated. Garmin's Autonomí [51] technology builds on the already existing automation of flight and adds a layer of decision-making, thus going beyond automating flight mechanics. Despite Garmin's progress, automated decision-making systems are limited in their ability to perform because of the lack of an over-arching operational concept, regulatory support, and compatibility with other traffic and controlling infrastructure. The paths therefore focus heavily on the automation of decision-making, and on the integration of autonomous decision-making systems in the NAS.
8. **The paths address functions for aircraft that are airborne**. This means that paths consider functions for air navigation, capabilities assessment, or communications rather than taxiing or cargo handling. These "ground functions" are left for a later study.

Methodology Discussion

This section provides in-depth discussions on each step of the method. It presents four use cases, analyzes airspace and regulatory constraints, layers the functions discussed in section 1, and surveys the technological state of the art.

Step 1 – Business and Use Case Identification

The use case defines an environment that provides the context to execute steps 2, 3 and 4 of the method to generate a path to autonomy. To properly understand the constraints placed on the vehicle and the operation by airspace and regulations, an environment must first be defined. Environment definitions include factors such as different classes of airspace, topography, weather, infrastructure, population density, and type of vehicle involved. These data then provide the required information for a functions and technologies analysis.

A use case cannot meaningfully be defined if a business case is not first identified. The reason for this is simple; technological development and certification are expensive, time consuming activities that are justified if their success leads to a future financial benefit, or to an equitable gain in society's quality of life. In addition, a successful use case considers present day regulatory realities, and leads to an evolutionary timeline that the FAA can support. This implies that the resulting path may not be the most direct path to achieving a business objective, but is one that the FAA can support given existing regulatory processes and technology readiness. The regulator and industry must work cooperatively to resolve potential disconnects between the paths industry may want to follow, and those the FAA may consider likelier to succeed.

Finally, automation must be implemented gradually from low risk to high risk use cases as confidence in the enabling technologies grows, and as experiential data is collected. This point is of crucial importance for novel technologies such as electric propulsion and non-deterministic systems; there is no replacement for flight hours. Again, the FAA and industry must work cooperatively. Industry should operate with the required transparency so that the FAA can fully understand what it is attempting to achieve, and the FAA should proactively find ways to allow the collection of flight data. Regulatory change has seldom happened before technologies have had the opportunity to prove themselves.

Four use cases (and four subsequent paths) are presented in the Paths Analysis section below. Each path leads to autonomy in a particular environment for a particular mission. The paths build upon each other from low to high risk use cases. The four use cases discussed are shown in Figure 8.

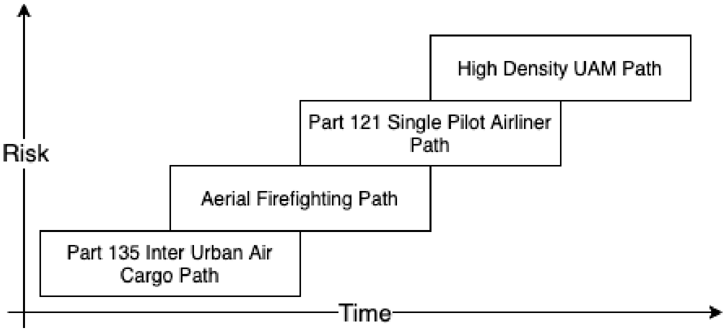


Figure 8: Four sample paths to autonomy

Step 2 – Airspace and Regulations Analysis

Airspace

A first step to enabling operational autonomy is to analyze the airspace in which exploratory DFR operations can initially be carried out. The following discussion aims to analyze the impact of decentralized decision-making authority by qualifying the airspace. Through a discussion about existing airspace environments, different airspace concepts put forward by the aviation community are presented. The analysis begins by identifying existing airspace strata in which operations could operate with minimal ATC interaction *in the present day*, as a precursor to the implementation of DFR, since DFR does not currently exist. Four airspace scenarios are considered:

1. Dense Urban – corresponding to Mature UAM operations *within* a single contiguous urban area, typically associated with Class B airspace.
2. Mixed Urban and Rural – similar to a hub and spoke model for commuter flights
3. High Altitude Airspace
4. Terminal Airspace

These scenarios are presented beginning with the most complex – the dense urban environment – followed by a series of simplifications that make the problem more tractable and easier to implement in the short-term in a progressive fashion.

Dense Urban Airspace

Regions within the 30 nautical mile Mode C veil of class B airports is taken as reference for the purpose of distinguishing between dense urban areas and "other" urban areas. In the United States, most airspace above 700 ft (Above Ground Level) AGL is controlled and extends to an unlimited ceiling. 14 CFR §107.51 specifies that small Unmanned Aircraft System (sUAS) must be operated below 400 ft AGL unless they are operated within 400 ft of a structure. These regulations dovetail into those prescribing minimum safe altitudes for fixed wing aircraft. 14 CFR §91.119 require that, in congested areas, fixed wing aircraft remain 1000 ft above the highest obstacles within a horizontal radius of 2000 ft. In any other airspace, fixed wing aircraft are simply required to remain 500 ft away from any person, vessel, vehicle, or structure. Additionally, 14 CFR §77.9 requires that any obstacle that is taller than 200 ft AGL be declared, though Part 77 also lists many conditions which would require shorter structures be declared. Figure 9 shows a side view of these distance requirements for a densely populated area.

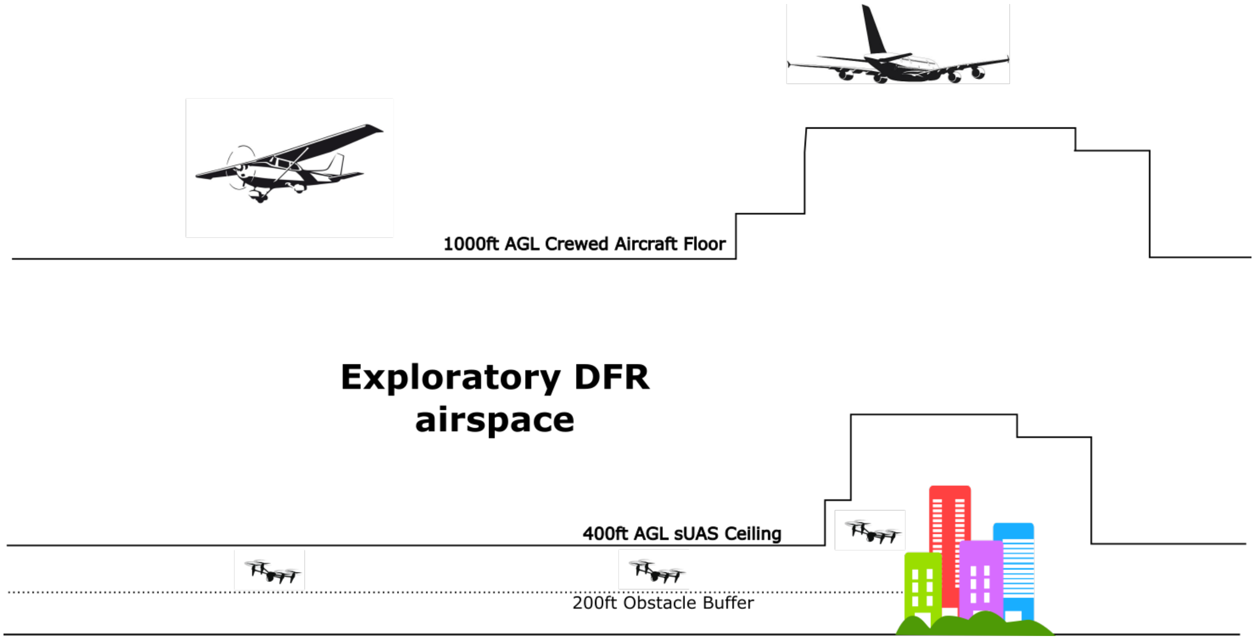


Figure 9: Urban airspace side view

In densely populated urban areas, altitudes between 400 and 1000AGL are therefore clear of aircraft. The regulations leave 600 ft of vertical empty space in congested areas (i.e., in dense urban centers), which makes it candidate airspace for exploratory DFR operations.

Despite this vertical empty space, complex existing airspace structures such as Class B and C impose lateral limits on exploratory DFR operations due to the existing operational requirements, which will need to be resolved in the long term. Class B and C airspaces are structured as "upside down wedding cakes," with an initial "core" of airspace from the surface to a specific altitude, and subsequent "shelves" staked on-top with larger radii. Within these airspace classes, aircraft are operating on an ATC clearance and are required to communicate to transition to and from airports. Limiting exploratory DFR operations to altitudes lower than 1000 ft AGL generally avoids these crowded “upper shelves,” subsequently unlocking greater swaths of airspace for DFR operations without conflicting with existing airspace delimitations and their associated clearance and communication requirements. It is also assumed that between 400 and 1000, every aircraft operating DFR will have a 100% complete traffic picture. Nonetheless, as shown in Figure 10, these existing airspace structures limit exploratory DFR operations to a relatively thin cross-section of the airspace. Once DFR has been implemented in “DFR-friendly” airspace, procedures would have to be developed to allow DFR aircraft to transition through B and C core and D airspace which extends to the surface.

Consider a flight in the San Francisco Bay Area departing from San Jose (lower right corner) towards downtown San Francisco (upper left corner).

Figure 10: San Francisco Bay Area [900 nm2] (left) and Dallas Fort Worth [2500 nm2] (right) airspace top view. Dark shaded areas represent core (to the surface) airspace which require a clearance and communication to operate within them. San Francisco top view is approximately 30 by 30 nautical miles (900 nm2). Dallas Fort Worth is approximately 50 by 50 nautical miles (2500 nm^2)

At any altitude above 1000 ft AGL, VFR and IFR operations prevail in the short-term, and in light of the sixth assumption, future DFR aircraft should be required to comply with ATC instructions to minimize disruption to the current air traffic management system. ATC compliance above 1000 ft AGL ensures that two agents (the aircraft and ATC) do not both have the responsibility for collision avoidance. It also simplifies the general communications problem as IFR, VFR and DFR aircraft would not have to communicate with each other to coordinate trajectory management tasks. Without initially completely redesigning the existing airspace boundaries, the following candidate strategies address implementing DFR in dense urban airspace. The options are presented in order of ease of implementation:

1. Comply with ATC instructions
2. Define designated airways for DFR aircraft, in the same way that VFR flyways are implemented today

3. Define Special Flight Rules Areas (SFRA) and Special Air Traffic Rules (SATR). Regulations such as 14 CFR §93.65 or §93.95 define particular rules aircraft must follow in particular locations.
4. Redefine airspace boundaries and/or airspace requirements.

Given these airspace constraints, operations above urban areas could be stratified as follows:

1. Crewed aircraft could operate in the 400 ft – 1000 ft AGL band under DFR, provided the crews are properly trained, and the aircraft can maintain a 100% complete traffic picture;
2. Un-crewed aircraft could operate DFR in the 400 ft – 1000 ft AGL band, and self-separate with other DFR aircraft (crewed or autonomous). Once again this assumes a 100% complete traffic picture; and
3. Crewed and un-crewed aircraft could operate above 1000 ft AGL and in core airspace in one of three ways:
    a. DFR: a DFR capable aircraft is not limited by "VFR" flight visibility requirements and has general "DFR" authority over its trajectory but must nonetheless be "VFR" cooperative and communicate with ATC when required;
    b. IFR: as operated today; and
    c. VFR: as operated today.

Mixed Urban & Rural Airspace

Rural areas typically have significantly lower traffic densities and simpler airspace structures. Consider the Burlington area shown in Figure 11. Outside class C, classes E and G prevail, and even though class E is controlled airspace, a clearance is not required to enter it and there are no communication requirements. Maintaining the same level of flexibility in the Bay and Dallas Areas is achievable, but would lead to much less direct and impractical routings which may force vehicles "into the system," requiring flight plans, clearances, and communications with ATC. The following tables provide a final point of comparison between the three sample areas discussed. Table 1 through Table 4 summarize the number of daily operations for the Class B, C and D airports located in the areas of Figure 10, and all airports located in the area depicted in Figure 11. The data is extracted from the FAA's Airport Data Information Portal for the year 2019. The average number of daily operations per airport is provided to convey a rough estimate of how "busy" each area is.

Table 1: Number of average daily operations in one year at each airport in the San Francisco Bay Area

Airport	RHV	SJC	NUQ	PAO	SQL	SFO	HAF	OAK	HWD	LVK
Number of daily operations	573	568	-	525	318	1255	137	651	320	424

Table 2: Number of average daily operations in one year at each airport in the Dallas Fort Worth Area

Airport	FWS	FTW	GKY	GPM	AFW	DTO	TKI	ADS	HQZ	RBD	DFW
Number of daily operations	192	373	242	180	308	452	298	334	143	118	1941

Table 3: Number of average daily operations in one year at each airport in the Burlington Area

Airport	PBG	BTV	FSO	MVL	MPV

Number of daily operations	33	200	19	11	28

Table 4: Total operations per area

	San Francisco Bay Area	Dallas Fort Worth Area	Burlington Area
Total Daily Operations	4771	4581	291
Daily operations per square mile	5.3	1.8	0.1

These low-density airspace and population areas would be ideal for trialing new autonomous technologies and DFR procedures.

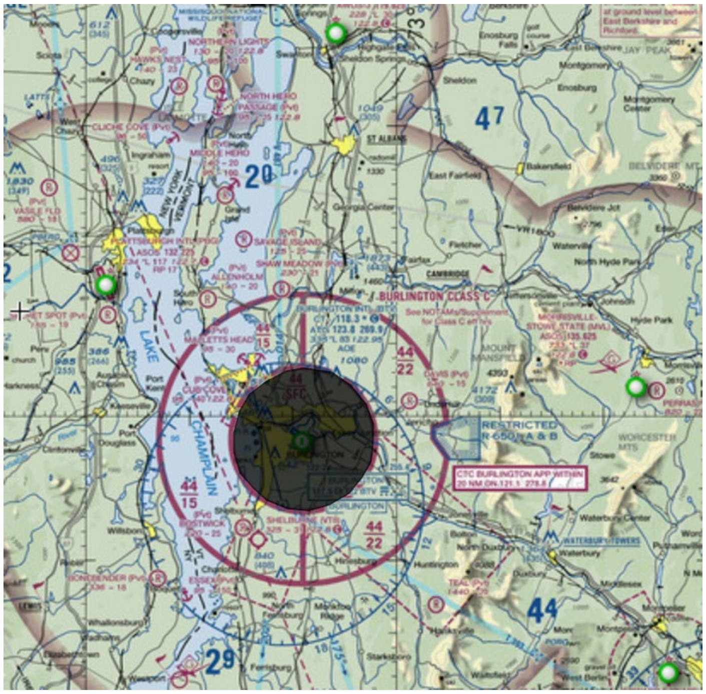


Figure 11: Burlington Area airspace top view. Dark shaded area represents the Burlington Class C core airspace. The top view is approximately 50 by 50 nautical miles (2500 nm2)

High Altitude Airspace

For the purposes of the analysis, high altitude airspace addresses long range operations between city pairs, typically served by large air carriers. Analysis of high altitude airspace reveals "DFR friendly" strata equivalent to the dense urban DFR zones identified in Figure 9. As discussed above, a key premise for DFR is a 100% complete traffic picture, and this is only achievable in the current environment through ADS-B. Figure 12 shows the current structure of ADS-B and controlled airspace.

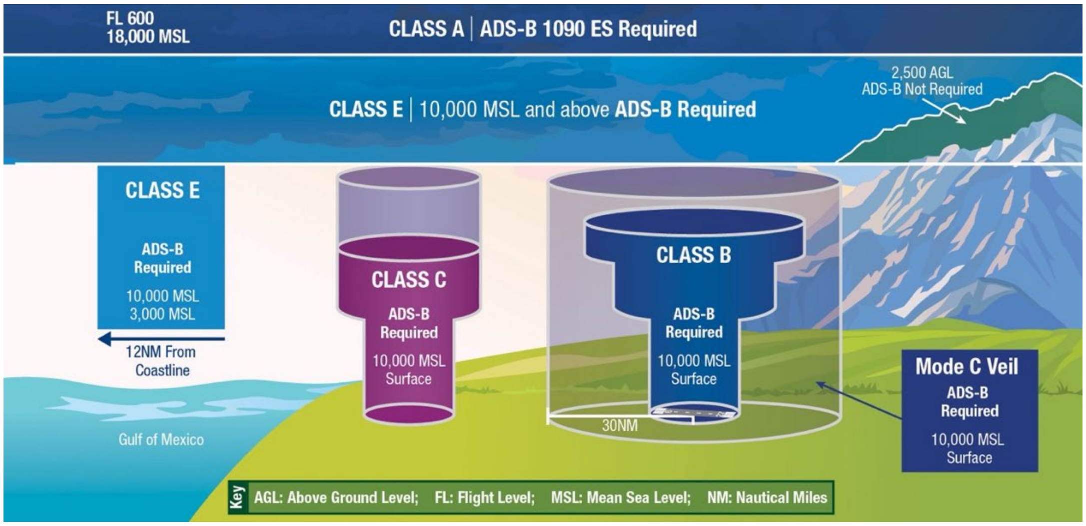


Figure 12: Airspace in which ADS-B is required [17]

As Figure 12 shows, 18000 ft MSL represents a cap for non-controlled (i.e., VFR and DFR) operations. Conversely, ADS-B coverage is not guaranteed below 10000 ft MSL, which would impose stringent onboard traffic detection requirements to assure the traffic separation function. Accordingly, the quickest implementation for DFR high altitude operations would be in airspace where ADS-B is mandatory while ATC clearances are not. This would constrain *initial* DFR crewed autonomous operations to class E airspace between 10000 ft MSL (minimum 2500 ft AGL) to 18000 ft MSL. The lower limit is defined by the mandatory ADS-B requirements of 14 CFR 91.225, as shown in Figure 13. It follows that aircraft operating above 10000 ft MSL and 2500 ft AGL have complete traffic DFV. The ceiling is set to below 18000 ft MSL because class A airspace starts at that altitude, with the attendant requirement for flight plans and ATC clearances.

Figure 13 includes oxygen requirements for unpressurized aircraft as an additional organizing factor, where aircraft without supplemental oxygen do not have access to altitudes above 12500 and below 14000 for more than 30 minutes, while oxygen-equipped and pressurized aircraft may operate anywhere within the class E band.

Until class A regulations are amended, and ADS-B requirements extended to the surface in all areas, initial DFR operations would likely be limited to altitudes below 18000 ft MSL and above 10000 ft MSL in the high altitude enroute airspace.

The VFR-on-top concept sets a precedent for reaching the DFR Operations Altitude Range (DOAR). With an ATC clearance to “climb to VFR-On-Top,” aircraft may operate IFR until they reach a suitable altitude where they are able to maintain VFR visibility requirements. Similarly, an aircraft could request a “climb to the DOAR.” The initial climb would be performed under VFR or IFR for traffic avoidance (since ADS-B is not guaranteed under 10000MSL), and upon reaching the DOAR, the vehicle could then continue DFR. The choice to depart VFR or IFR is at a minimum a function of the prevailing weather conditions under the DOAR and the airspace classes of the departure and destination airfields or vertiports.

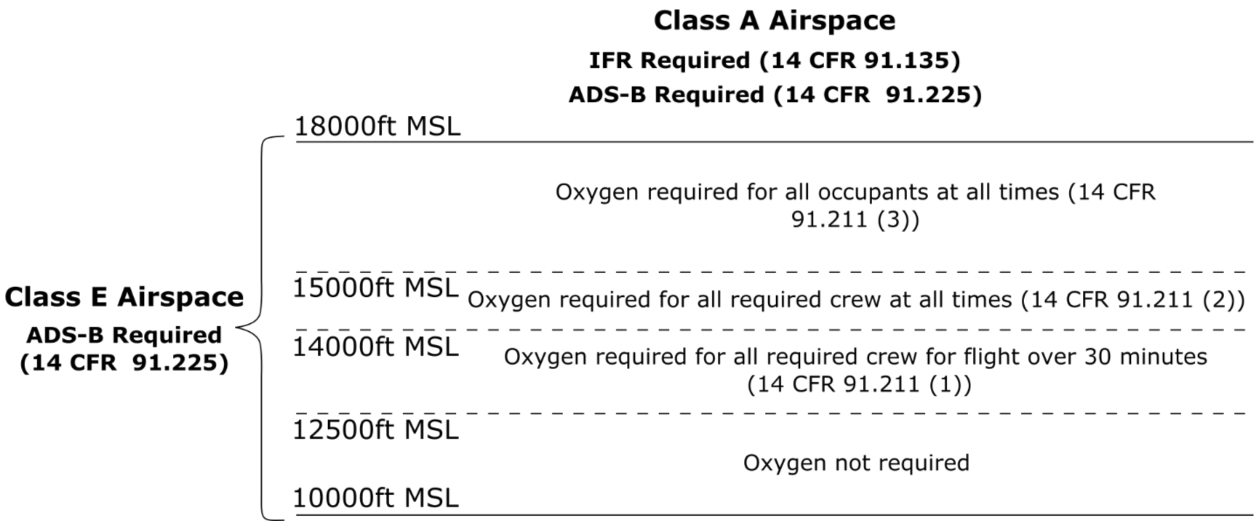


Figure 13: Class E airspace for DFR operations at or above 10000 ft MSL and below 18000 ft MSL. Supplemental oxygen requirements are included as an additional organizing factor.

In the DOAR, the concepts of IMC and VMC do not apply, since these are rooted in human visual perception, which is irrelevant for sensor based and data-linked data. In DFR, flight visibility is replaced by the concept of DFV, a minimum level of which is required to operate DFR. Given a sufficient level of DFV, a crewed vehicle with no windows could operate under DFR.

To enable DFR operations in the DOAR, three initial regulatory avenues have been identified:

1. Restricted Category: Under 14 CFR § 21.25, an *"applicant is entitled to a type certificate for an aircraft in the restricted category for special purpose operations,"* within special conditions granted by the FAA. § 21.25 (1) also specifies that aircraft to be used must meet *"the airworthiness requirements of an aircraft category except those requirements that the FAA finds inappropriate for the special purpose for which the aircraft is to be used."* For example, firefighting aircraft need not comply with Part 36 noise requirements given the nature of their operation. The restricted category therefore offers some flexibility in meeting airworthiness requirements as well as creating provisions for special types of operations, such as DFR, which would have to be added to the list in § 21.25 (b).
2. Experimental Category: Under 14 CFR 21.191, an experimental certificate may be issued for testing "new aircraft operating techniques, or new uses for aircraft." Experimental flight permits could be obtained to test new DFR procedures.
3. Special Flight Permit: Though special flight permits are generally issued for ferry flights, overweight flights, or other flights of similar nature (14 CFR § 21.197), Order 8130.34D states that *"[t]he FAA will continue to evaluate the need to further expand the purposes for which special flight permits will be issued to UAS, [Optionally Piloted Aircraft] OPA, and OPA/UAS under § 21.197."*

Initially, DOAR operations are likeliest to be approved for Part 91 or Part 135 cargo operations in sparsely occupied airspace. Aircraft equipped with traffic avoidance systems that can communicate their trajectory intent to ATC would have access to this airspace, and trajectory optimizers that account for traffic and other hazards would facilitate such operations. DOAR operations would initially provide the industry and the regulator with key information on how to integrate operationally autonomous aircraft in the NAS, without the added complexity of crewless or remotely piloted aircraft and the certification of the associated technologies. This approach effectively dissociates the technological challenges associated with crewless aircraft from the implementation challenges associated with operating autonomously, by leveraging systems already certified for use or that have already been extensively tested.

The following inter-related factors dictate the feasibility of implementing DFR operations in today's airspace structures:

1. Intent Data: the ability of a vehicle to communicate its intended trajectory to ATC and other aircraft is imperative for cooperative airspace usage, particularly for electric vehicles and densely populated airspaces such as those envisioned for UAM;
2. Knowledge of capabilities: including real-time assessment of the vehicle's APP for electric vehicles. To make "smart" decisions, vehicles should be able to translate their system health into achievable trajectory objectives and outcomes; and
3. Digital Flight Visibility: a vehicle's decisions are made based on its situational awareness as discussed in the Functions Analysis in Section 1. Digital flight visibility is quite unlike visual perception, and there are already analogs in use today. Enhanced Flight Visibility has already been discussed, but a less obvious example is IFR flight operations. IFR pilots avoid terrain and obstacles by adhering to published minimum altitudes, such as MEAs, Minimum Obstacle Clearance Altitudes (MOCA), off-route obstruction clearance altitudes (OROCA), and approach procedure altitudes. These minimum altitudes, which do not comprise a visibility element, nevertheless act as proxies to the flight visibility used by a VFR pilot to avoid hazards.

Terminal Airspace

For the purposes of the analysis, terminal airspace addresses the special requirements for DFR operations in the terminal area which require integration with IFR and authorized VFR traffic. In IFR operations, aircraft follow published Standard Terminal Arrival Routes (STARs) to transition from the enroute air structure to the terminal air structure, and then follow instrument or visual approaches to the runway threshold. In the absence of STARs, aircraft generally follow vectors provided by ATC to the initial approach fix. These structured routings enable air traffic control to maintain a certain throughput at an airfield. Analogous to the STAR, Standard Instrument Departures (SID) are published routes that departing traffic follows to transition from the terminal area into the enroute air structure. At airports without a control tower, departure, arrival, or center control often does not have traffic visibility around the airport. Because of this, the arrival and departure of IFR traffic effectively closes the airport to other IFR traffic until the traffic in question becomes visible to approach, departure, or center control. This "one in, one out" mechanism throttles the airports throughput and limits airspace accessibility.

VFR operations are not subject to the limitations of IFR procedures. At controlled fields, VFR traffic simply arrives or departs on vectors or visual procedures using landmarks. At uncontrolled fields, traffic self-organizes by combining expected behavior with aircraft-to-aircraft coordination. The traffic pattern provides aircraft with a defined racetrack which they should use to transition to and from the field, and provides pilots with common vocabulary to locate themselves with respect to the airfield and other aircraft "in the pattern."

To start enabling an increase in airspace accessibility and operator flexibility, the focus is set on those fields not commonly used by large flagship carriers. In the United States, 70% of travelers utilize only 30 available airports [19]. As of May 20th, 2021, according to the FAA's Airport Data and Contact information database, there are 5050 operational public use airports (including heliports and seaplane bases) in the United States. Of these, 4500 do not have Air Traffic Control Towers (ATCT) [20], while 2500 have at least one instrument approach procedure [21], subjecting them to the "one in, one out" IFR paradigm.

To enable an increase in airport utilization, aircraft must be able to fly to and from airports in all weather conditions without the delays incurred by the lack of ATC visibility into the airport's overlying and surrounding airspace. To achieve this goal, either more air traffic control towers should be put in service (the FAA closed 149 towers in 2013 [22]) or alternative traffic management methods established. Complementarily, more instrument approach procedures should be published.

In 2002, NASA studied a concept named Small Aircraft Transportation System, Higher Volume Operations (SATS HVO) which would enable aircraft in instrument conditions to execute approaches without supervision and direction of center control. The concept provides a candidate solution to replace the "one in, one out" method without incurring the costly investments required to build control towers and their associated infrastructure. In SATS HVO, IFR aircraft request an approach clearance from an automated Airport Management Module (AMM). The AMM provides approach sequencing to Initial Approach Fixes (IAFs) through lateral or vertical clearances, as shown in Figure 14.

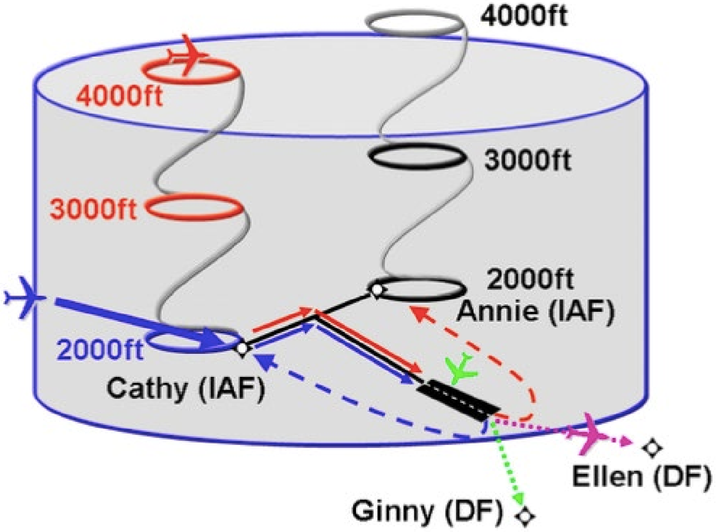
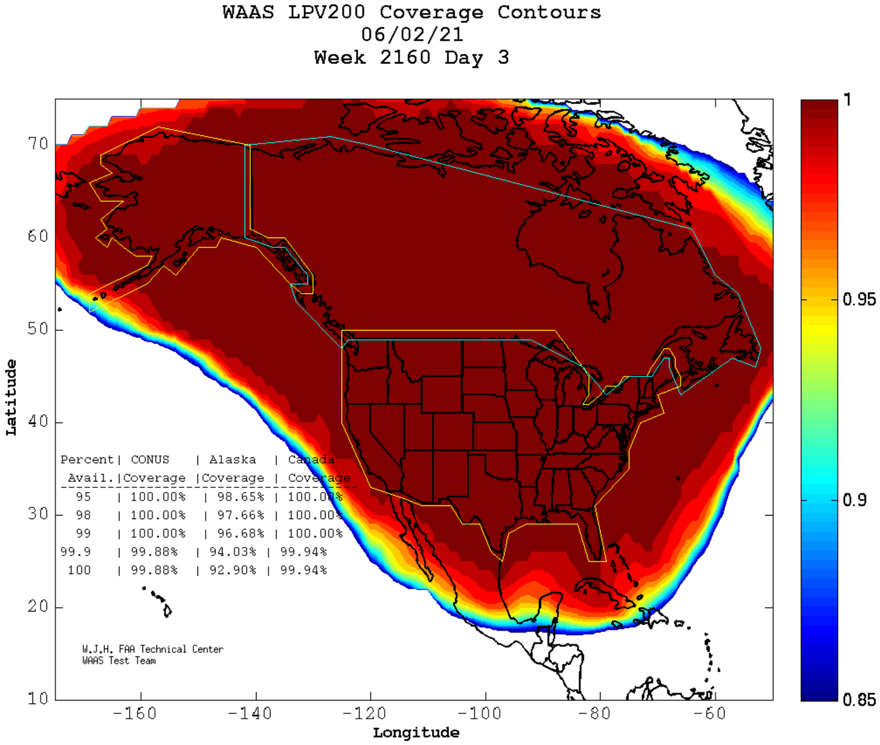


Figure 14: SATS HVO airspace concept [23]. The Blue aircraft is granted a lateral clearance to Cathy, and the Red aircraft a vertical clearance to Cathy. As the Blue initiates its approach, Red is cleared by the AMM to descend through the stacked holding patterns follow blue

Participating aircraft must be capable of detecting other traffic, sending, and receiving messages to and from the AMM, and following other aircraft. In crewed situations, particular avionics solutions will be required to display these data, for which initial concepts have been provided [23]. Additional work on designing avionics solutions has been carried out by a team of researchers at Texas A&M, who designed moving map and heads up displays to aid the pilots in decision-making and situational awareness while executing SATS HVO procedures [29]. The SATS HVO concept also outlines procedures for departures and missed approaches and was initially designed around the assumption that aircraft are arriving and departing under IFR. A 2005 feasibility assessment of the SATS HVO concept conducted by the FAA showed the concept has promise. The study included air traffic controllers and pilots, all operating in a simulated environment of the Philadelphia and Danville areas. The assessment concluded that further research is required (e.g., phraseology, location of SATS airports), but that it worked best in uncongested areas, significantly increasing throughput at the airport [30]. Given the AAM vision, an expansion of this concept and continued research based on the FAA assessment findings would be relevant.

To enable widespread adoption of SATS HVO-type procedures, the number of airports with instrument approach procedures should also be expanded. Wide Area Augmentation Services Localizer Performance with Vertical Guidance approaches (WAAS LPV) provide a cost-effective solution to this problem. The WAAS infrastructure provides LPV services to any properly equipped aircraft without requiring physical instrument approach infrastructure at the airport, and does so with a fixed number of ground-based facilities and geo-stationary satellites [26]. Figure 15 shows LPV service coverage for the United States and Canada. Even though the airfield in question must comply with certain design requirements [24] (e.g., parallel taxiway, runway markings, obstacle clearance), costly Instrument Landing System (ILS) and glideslope antennae for each approach are not required. Instead, the approach is defined by GPS waypoints, and is flown with Technical Standard Order (TSO)-C145/146 airborne equipment. An example of TSO-C146 equipment is the widely used Garmin Navigation System (GNS) 430W or 530W. LPV approaches have increased accessibility for regional and commuter operators such as Horizon and Cape Air [27].



Percent Avail.	CONUS Coverage	Alaska Coverage	Canada Coverage
95	100.00%	98.65%	100.00%
98	100.00%	97.66%	100.00%
99	100.00%	96.68%	100.00%
99.9	99.88%	94.03%	99.94%
100	99.88%	92.90%	99.94%

Figure 15: WAAS LPV200 coverage contours at the time of writing [25]. The chart shows that LPV approaches down to 200 ft minimums were available for 95% of Day 3 of week 2160 for 100% of the CONUS. Conversely, for 100% of the same time frame, 99.88% of the CONUS had access to LPV200 approaches. The color bar shows the percent of WAAS LPV200 coverage.

Field testing concepts such as SATS HVO has the advantage of testing autonomous operations under DFR, as would be carried out in the DOAR, but in the terminal environment. The approach is supported by a recent NASA initiative termed Regional Air Mobility (RAM) [19], which identifies potential business cases for point-to-point cargo and passenger travel.

Airworthiness Certification

This section addresses situations where a vehicle or technology does not strictly adhere to the relevant airworthiness regulations, or, conversely, the current regulations do not support the functions performed by the vehicle. Three Parts of 14 CFR are particularly applicable: 14 CFR § 1.1 *General Definitions*; 14 CFR § 11 *General Rulemaking Procedures*, and 14 CFR § 21 *Certification Procedures for Products And Articles*.

14 CFR § 1.1 General Definitions

The importance of 14 CFR § 1.1 is best illustrated by example: the benefits of Enhanced Vision Systems (EVS) for reducing approach minima could not be realized with the legacy definition of *Flight Visibility* as *"the average forward horizontal distance, from the cockpit of an aircraft in flight, at which prominent unlighted objects may be seen and identified by day and prominent lighted objects may be seen and identified by night."* EVS was accommodated with a newly-defined *Enhanced flight visibility* (EFV) as *"the average forward horizontal distance, from the cockpit of an aircraft in flight, at which prominent topographical objects may be clearly distinguished and identified by day or night by a pilot using an enhanced flight vision system"* (emphasis added). The distinction is not purely semantic, because the definitions form part of the regulations that incorporate them. Pilots could simply not treat EFV as Flight Visibility for the purposes of gaining operational credit without the new definition. This situation could arise with several of the concepts introduced in this paper, including DFR, DFV, and definitions associated with Artificial Intelligence (AI) decision-making, such as DMS.

One obvious definitional road-block for unpiloted vehicle relates to the use of the "pilot" in 14 CFR § 91. ASTM has evaluated this Part to determine the impact of the pilot being "hard-wired" into the regulation, as shown in the following chart.

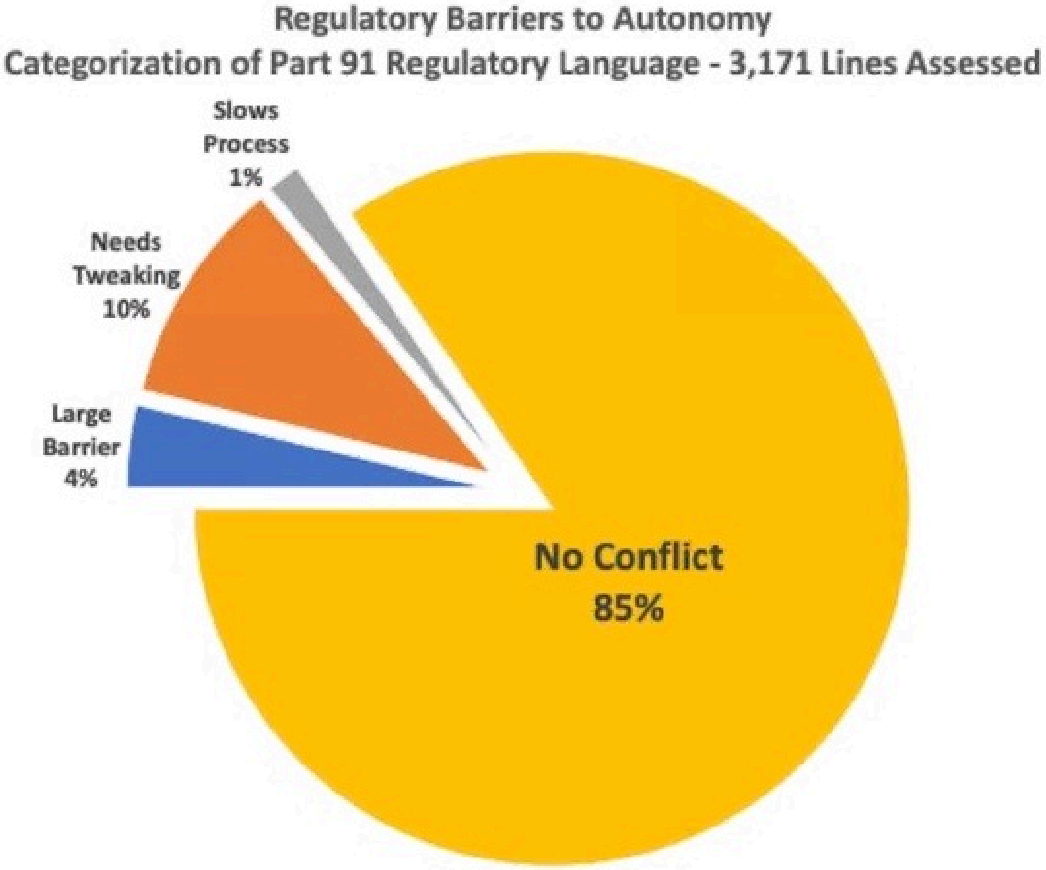


Figure 16: ASTM Part 91 regulations analysis

As the figure shows, there was no conflict for 85% of the Part 91 regulations, and a "Large Barrier" was only noted for 4% of the rules. Of the remainder, 10% "need tweaking" and 1% "slows process." Of the identified "problem rules," the majority related to explicit mentions of the pilot and pilot functions. It should be noted that this review was constrained to the General Operating and Flight rules of Part 91, and it should be expected that the commercial and Air Transport rules of Parts 135 and 121 will doubtless be far more restrictive. For example, 14 CFR § 121.385(c) explicitly states "*the minimum pilot crew is two pilots...*" for scheduled air carrier operations.

The latter would either require a technology increment to allow the Garmin system to respond to ATC instructions, or a change in this rule, which requires compliance with ATC clearances. In either event, this simple example highlights the technology and regulatory disconnect that has been identified by the application of the proposed method.

14 CFR § 11 General Rulemaking Procedure

Once the need to change a regulation has been identified, the available options are defined in this Part, which details the processes for petitioning the FAA to adopt, amend, or repeal a regulation, or grant relief from the requirements of a current regulation. The applicable regulations state:

§11.15 What is a petition for exemption?

"A petition for exemption is a request to the FAA by an individual or entity asking for relief from the requirements of a current regulation."

Petitions for exemption are submitted through the Airworthiness Certification Office (ACO) for public comment, and the requested exemption must benefit the public as a whole and, either: not adversely affect safety or, would provide a level of safety at least equal to that provided by the rule from which relief is sought.

These *are* the criteria against which any airworthiness exemptions would be granted, so they must be integral to the Paths planning activity.

§11.17 What is a petition for rulemaking?

"A petition for rulemaking is a request to FAA by an individual or entity asking the FAA to adopt, amend, or repeal a regulation."

In order to decide whether the preceding provisions should be invoked, it is necessary to examine the applicability of the existing regulations. For airworthiness certification, these are contained in 14 CFR § 21.

14 CFR § 21 Certification Procedures for Products and Articles

Type Certification for normal, utility, acrobatic, commuter, and transport category aircraft, is generally by 14 CFR § 21.21, which points to the familiar Parts 23, 25, 27 and 29. Some UAM vehicles, such as Powered-lift aircraft straddle these categories, such as Parts 23 and 27, and may possess some features, such as parachute recovery systems, that fall outside any of these rules. In this event, 14 CFR § 21.17(b) governs:

14 CFR § 21.17(b) Designation of applicable regulations:

> "For special classes of aircraft, including the engines and propellers installed thereon (e.g., gliders, airships, and other nonconventional aircraft), for which airworthiness standards have not been issued under this subchapter, the applicable requirements will be the portions of those other airworthiness requirements contained in Parts 23, 25, 27, 29, 31, 33, and 35 found by the FAA to be appropriate for the aircraft and applicable to a specific type design, or such airworthiness criteria as the FAA may find provide an equivalent level of safety to those parts."

In other words, the evolving Paths can choose from *any* of the existing regulations that the FAA finds "appropriate" to the vehicles intended function, as long as an equivalent levels of safety can be shown.

Garmin’s Autonomí™ system takes advantage of similar provisions when it invokes emergency authority under 14 CFR § 91.123. The system accomplishes this by declaring an emergency over voice channels, so no fundamental regulatory changes were required to implement this function. If, however, the system were to be extended to non-emergency operations, a number of regulations would have to change, such as 14 CFR § 135.99 *Composition of flight crew* and 14 CFR § 91.123 *Compliance with ATC clearances and instructions*.

The final case concerns an area where *no* applicable regulation exists, which is covered by *Special Conditions* which returns the discussion to 14 CFR §11*.*

14 CFR §11.19 What is a special condition?

“A special condition is a regulation that applies to a particular aircraft design. The FAA issues special conditions when we find that the airworthiness regulations for an aircraft, aircraft engine, or propeller design do not contain adequate or appropriate safety standards, because of a novel or unusual design feature.”

Unique design features, *for which no regulations exist*, are initially covered by Special Conditions, until sufficient operational experience is obtained to migrate the Special Condition into the main body of the regulations. Examples of FAA Special Conditions pertinent to the UAM scenarios include whole-aircraft parachutes and Garmin’s Autonomí™ autoland system. The European Aviation Safety Agency (EASA) has even produced Special Condition SC-VTOL-01 to specifically address novel distributed lift/thrust units that generate powered lift and control, as well as vehicles that might be unable to perform an autorotation or a controlled glide in the event of a loss of lift or thrust.

Almost all major AI decision-making functions would fall under the Special Condition category, because existing regulations were not conceived for non-deterministic systems. The most feasible approach is to bound the non-deterministic function using a simple deterministic controller. ASTM Standard Practice F3269–17 *Methods to Safely Bound Flight Behavior of Unmanned Aircraft Systems Containing Complex Functions* defines a Recovery Control Function (RCF) which performs exactly this task. If comprehensive data-mining techniques are applied, it is foreseeable that sufficient statistical confidence could be achieved with the non-deterministic parent system that the RCF could be given decreasing authority, eventually being eliminated altogether. We have seen such a migration as automation, properly implemented, has reduced airliner cockpit crews from five to two, even as the capabilities of their aircraft have increased by several-fold.

The flowchart in Figure 17 shows which processes should be applied whether a regulation exists, and if compliance is possible.

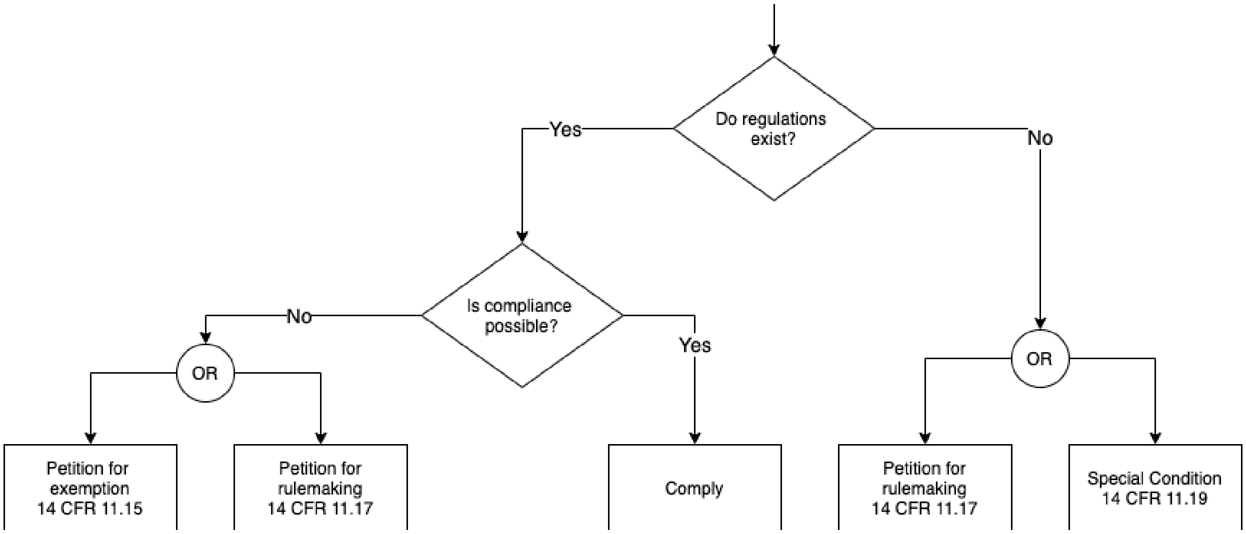


Figure 17: Regulatory processes

Consensus Standards

A critical regulatory (r)evolution concerns the FAA's adoption of consensus standards developed by ASTM for Part 23 aircraft (Committee F44) and unmanned aircraft systems (Committee F38). These standards respond directly to industry needs and are also performance based, rather than being prescriptive. Both of these characteristics are highly desirable for the Paths to Autonomy effort because DFR and its associated regulations must be performance-based rather than prescriptive. In DFR, aircraft should have authority over their own trajectory in all weather conditions. Regulating DFR in terms of miles of optical "Flight Visibility" is not applicable if the aircraft uses ADS-B, radar sensors, and databases to detect traffic, weather, and terrain respectively. Optical visibility has no meaningful impact on the vehicle's ability to perform its mission, if it does not use optical sensors to detect its environment. This is perhaps the biggest regulatory challenge that has hamstrung earlier automation efforts, and which can be overcome by the use of performance based consensus standards.

Airworthiness Certification Mitigating Strategies

The following recommendations summarize the preceding airworthiness discussions, along with a way-ahead for minimizing the risk and time to adopt new required rules.

1. **New definitions required under 14 CFR § 1.1 should be identified as quickly as possible using a structured procedures such as those introduced in this paper. Certification authorities and industry groups such as ASTM should be engaged swiftly to start implementing the necessary changes so that they will already be part of the rule basis when the technology is available to benefit from them.**
2. **Emerging technologies and procedures should be mapped to existing 14 CFR Parts § 23, 25, 27, 29, 31, 33, and 35 to the maximum extent possible.**
3. **Existing Special Conditions should be leveraged to the greatest possible degree and new Special Conditions should be identified and pursued early in the product life-cycle.**
4. **Required exemptions should be identified and pursued early in the product life-cycle if it can be shown that the sought-for exemption will benefit the public as a whole and, either: not adversely affect safety or, would provide a level of safety at least equal to that provided by the rule from which relief is sought.**
5. **The requirement for new regulations, such as those pertaining to DFR and AI, should be identified and pursued early, to ensure that they have been enacted when the technology readiness level requires them to be in effect.**
6. **A formal program should be developed early in the product life-cycle to obtain quantified reliability and safety data for any new technologies or procedures. Data mining is a powerful tool that can substantially aid the certification authorities as they try to assess the risks associated with technological advancement. This data mining activity is particularly important for the implementation of non-deterministic AI functionally.**

Step 3 - Functions Layering

Section 1 derived a core-function superset that is common to all use cases, as listed in appendices B, C, D, E and F. Since the functions are “core”, each path discussed in the Paths Analysis section focuses on one aspect of the superset to avoid repeating all functions presented in this report for each path. However, nothing prohibits the stepped implementation of the entire superset in each individual path. On the contrary, this is encouraged as it makes the entire method more resilient if one path were to fail for any reason.

A high level depiction of the functions layering is shown in Figure 18, with the implementation stages on the x axis, and the implemented functions on the y axis. Each implementation stage consists of a “function group” which is composed of several “function blocks”. Blue boxes represent functions that are assistive only, and are ultimately the responsible of a human crew. Purple boxes represent functions that have sufficiently proven themselves and been certified as responsible; autonomous systems are responsible for their execution. Six stages are shown, but more may be required depending on the advancement of regulations, the quality of the collected experiential data, and the technological state of the art. In the event more stages are required, function groups and blocks may be broken apart to introduce the functions more gradually. The individual functions found in each function block are listed in appendices B, C, D, E, and F.

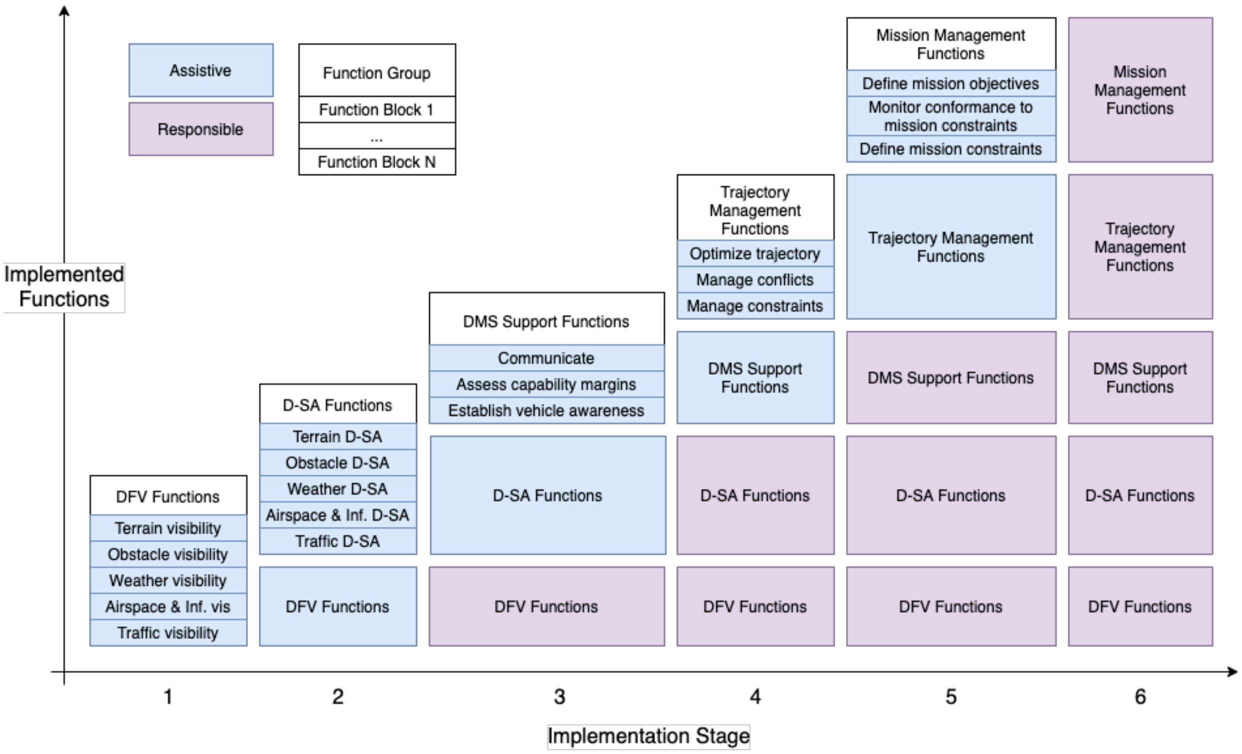


Figure 18: Functions implementation stages

Figure 18 provides a high level view of the order in which function groups and blocks should be implemented. However, the relationships between each individual function within each function block is not captured. Representing them in this format would quickly become difficult because of the large number of functions and interrelationships.

The functions ontology provides a better medium for capturing the relationships. Figure 19 shows an example of how the ontology tracks functional relationships for the “Traffic Visibility” function block shown in Figure 18. To successfully perform function A (boxed in a red dashed line), all functions upstream of it along the blue diamond-arrowhead line must be performed first, in order.

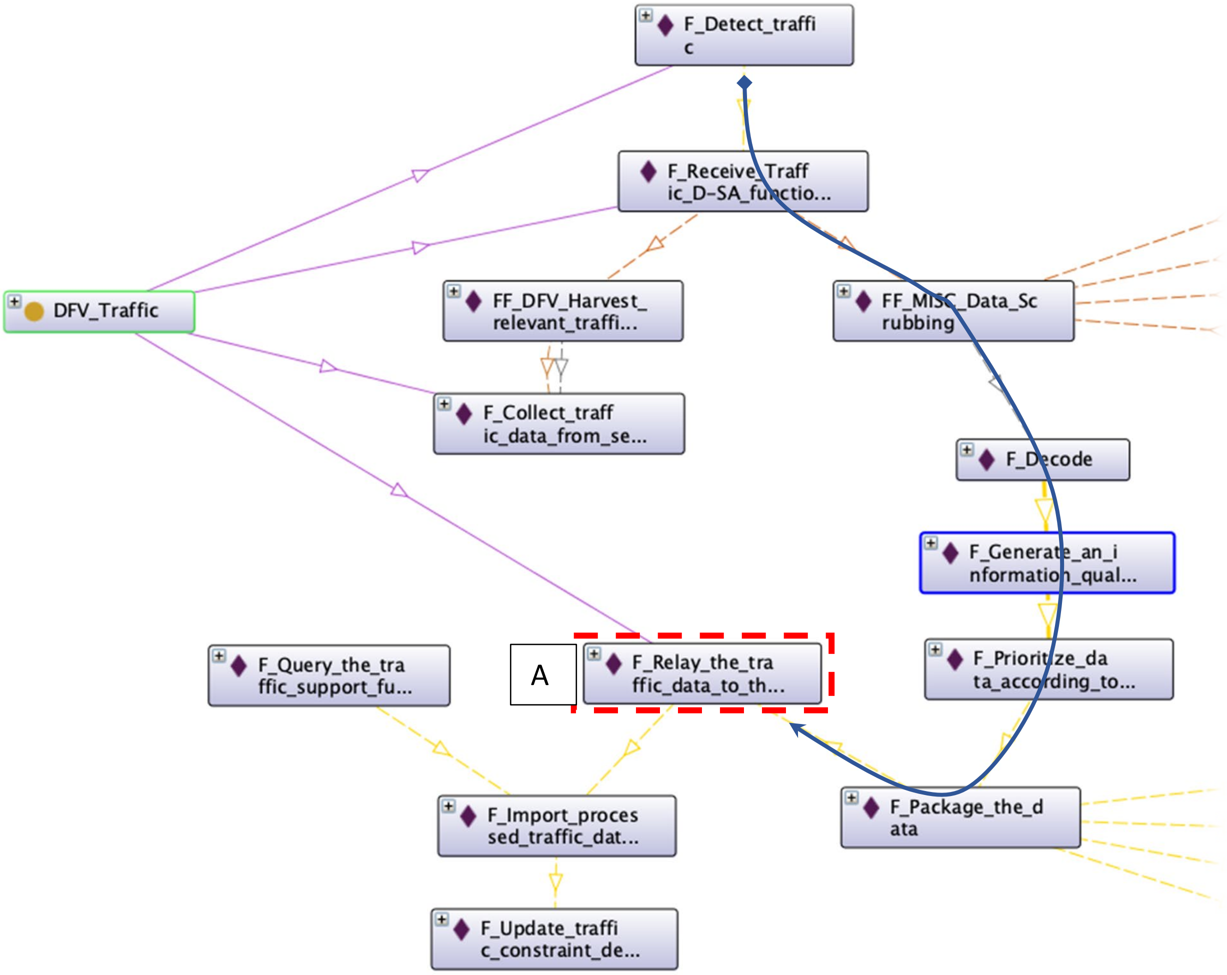


Figure 19: Traffic Visibility (DFV_Traffic) function block functional dependencies.

The ontology also tracks functional dependencies specified between function blocks in different function groups. Figure 20 shows an example of how the ontology tracks functional relationships between the "Traffic Visibility" and "Traffic D-SA" function blocks shown in Figure 18. To successfully perform function B (boxed in a red dashed line), all functions upstream of it along two independent blue diamond-arrowhead lines must be performed first, in order.

The ontology provides a scalable method to track many functional interrelationships. As functions are developed, the ontology can continue to be populated with more detailed functions. As more functions are added over time, their impact on the implementation paths can easily be evaluated.

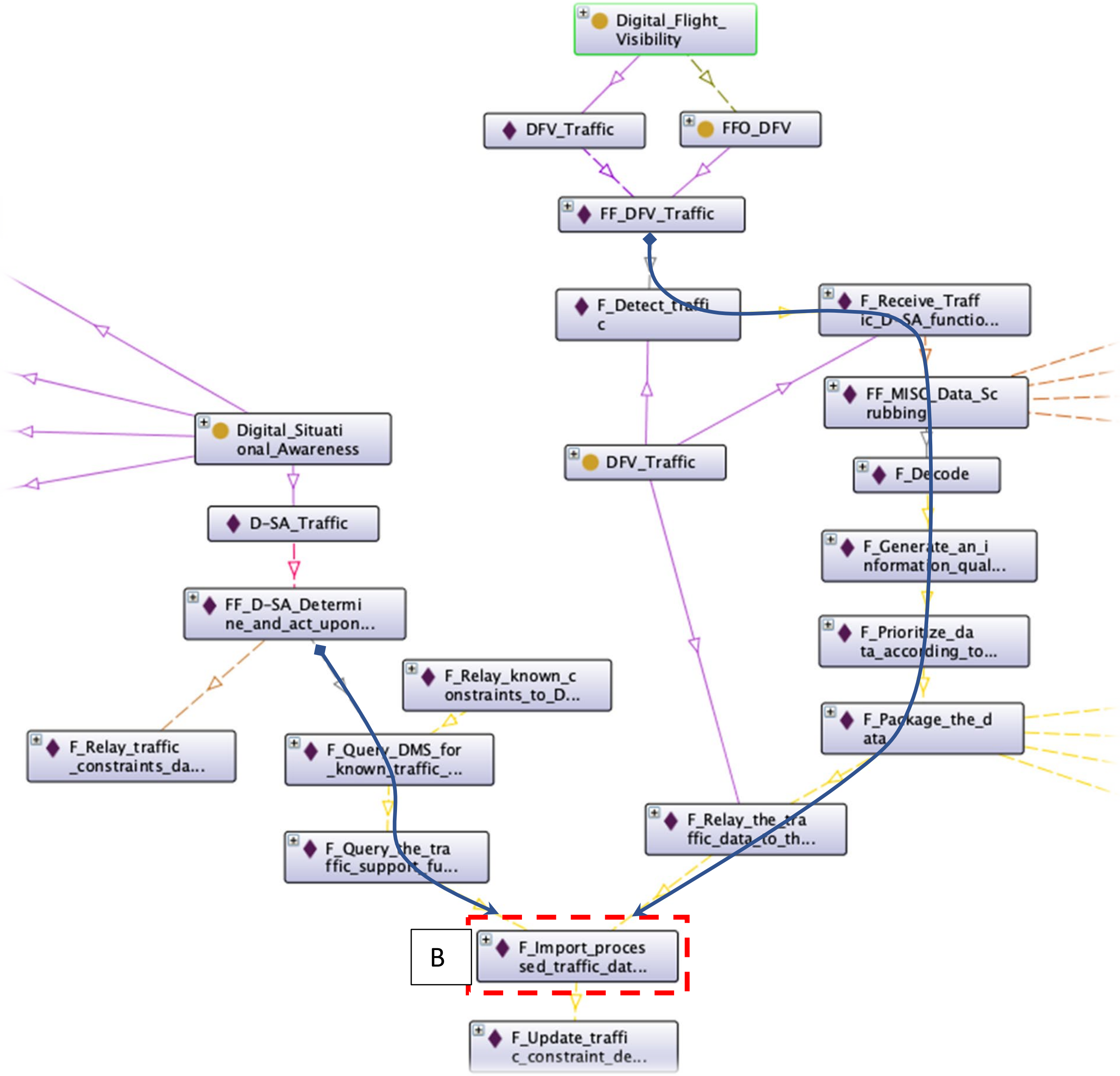


Figure 20: Traffic D-SA and Traffic Visibility function blocks dependencies

Step 4 – Technologies Analysis

Trajectory Management

In DFR, aircraft must deconflict their trajectories from all other traffic, just as VFR aircraft do when operating in uncontrolled airspace. Based on capabilities, DFV, and intent data, Vehicle-to-Vehicle (V2V) coordination could be achieved through priority rules, resulting in implicit maneuver coordination, or via handshaking their intents as currently conducted with TCAS Resolution Advisories. Based on these data, vehicles negotiating with a number of other vehicles will have to prioritize which vehicles to negotiate with first. In addition to negotiating based on intent data, consideration of capabilities and visibility may be required. Questions such as "who has better information?" or "who is most energy limited?" will need to be answered. The energy limitation is of particular importance for electric vehicles which are likely to be energy challenged.

TCAS-II and ACAS-X (under development) are retained as tactical safety nets. Depending on threshold traffic densities which will have to be experimentally determined, different negotiation strategies could be employed. It is foreseeable that in the short term, current right of way rules be amended for DFR to cater for eVTOL operations in high density areas. Two trajectory optimization technologies (TASAR and AOP) and two deconfliction strategies (RTA/Interval Management (IM), and swarming) are proposed that complement trajectory management by allocating functions from ATC to the cockpit.

1. Trajectory Management Automation

NASA’s Traffic Aware Strategic Aircrew Request (TASAR) and Autonomous Operations Planner (AOP) provide flight crews with on-board trajectory management capability. TASAR is a near-term deployable solution for trajectory optimizer (e.g., time and fuel) subject to constraints such as traffic, airspace, weather and wind [14]. TASAR was operationally tested with Alaska Airlines and has shown promise in its ability to deliver conflict-free route optimization [15]. Karr et al. [13] discuss a Pattern Based Genetic Algorithm (PBGA) capable of providing traffic avoidance maneuvers to crews while respecting an RTA constraint. The algorithm evaluates if, and where, a conflict will occur, and implements route changes through lateral and vertical offsets. At the time of writing, the system had performed successfully for traffic densities up to 12 times those seen in the enroute airspace, demonstrating its scalability. AOP is a far-term trajectory management capability that would support the functions required for mature DFR operations. These two technologies are potential enablers of the decentralization of trajectory management in the en-route airspace, but their implementation in environments such as high density urban requires them to be properly scaled to the constraints of those environments.

2. Deconfliction Strategies

The first of two deconfliction strategies entail the implementation of Required Time of Arrival (RTA) and Interval Management (IM) functions. As part of the FAA’s NextGen Air Transportation System (NextGen) to support increased traffic densities, Time Based Flow Management (TBFM) provides aircraft with guidance to meet specific arrival metering fixes at a specific time by leveraging their ability to fly precise routes consistently [5]. Part of this capability is Ground-based Interval Management Spacing (GIM-S), whose function is to space aircraft by a determined time interval. A counterpart to GIM-S, NASA’s Airborne Spacing for Terminal Arrival Routes (ASTAR) algorithm implements Flightdeck Interval Management (FIM). This on-board algorithm manages the speed of a following aircraft to merge it onto a route behind a leading aircraft, at a specific fix at a given time interval using ADS-B data [6]. The ASTAR algorithm was successfully tested in 2014 [7] and subsequently in the ATD-1 trials in 2017 [52]. Interval management has also been applied to Continuous Descent Approaches (CDA), to combine their relative energy efficiency with precision spacing [8]. This combination has been shown to be an energy efficient method for aircraft to transition from cruise to landing, while complying with RTA’s to within a few seconds, despite wind effects [9]. Precision spacing can be disrupted by convective weather, which in turn disrupts the planned metered flow of traffic to a given fix. Gong et al. address this issue with a system that generates Dynamic Arrival Routes (DAR). The generating algorithm predicts the need for weather related re-routes and suggests options early enough for scheduling systems to re-adjust estimated times of arrival. The algorithm currently does not consider RTA constraints, but this is the subject of future research [10]. The RTA concept has also been applied with success in 2D problem spaces, such as for taxi clearances. Bakowski et al. demonstrate that an error nulling algorithm outputting speed commands to flight crews enabled them to meet RTA's at runway thresholds within seconds [11].

Although the examples provided above are studied in the context of Part 25 "heavy" aircraft, the principles are transferable to UAM as the problem is simply one of scalability. In all cases, RTA and self-spacing increased traffic predictability, which when coupled with PBN have the potential of increasing traffic throughput in a given airspace. In fact, these are NextGen objectives. As described, these functions also have the effect of increasing flight efficiency, crucial to electric vehicles. Applied in urban contexts, vehicles could be issued RTA's to vertiports to guarantee airspace clearance for other aircraft. In-trail functions could enable queues of vehicles between different vertiports in which vehicles self-separate and target required arrival times. The traffic predictability enabled by these functions will likely reduce the unknowns in energy management and the amount of tactical deconfliction maneuvers, thereby increasing airspace safety.

Though these functions provide potential solutions to the complex urban traffic management problem, in-trail functions may imply aircraft are following each other on given routes, which can be seen as an impediment to the unfettered access demanded by DFR operations. These routes may be generated by an independent entity such as a PSU [12] or by vehicles organically organizing themselves along optimized paths. Either way, other technologies to generate these routes are required.

An initial step to testing the RTA and IM technologies described above would be to implement a "follow-the-leader" traffic control algorithm. Figure 21 shows flights from the western United States on June 3rd, 2021, to the Hawaiian Islands, arranged along two distinct flight corridors which merge at waypoint DIALO. Beyond DIALO, each flight continues to Hawaii along route R576. Rather than controlling each aircraft individually, ATC could issue RTA's to DIALO, or self-spacing instructions. Aircraft would then be in a queue and manage their speed to follow the lead aircraft. The additional responsibility of traffic avoidance can be transitioned to the crew by use of TASAR-like technologies to start implementing the concept of Distributed Air Ground Traffic Management (DAG-TM).

Figure 21: Flights from the West Coast to Hawaii (FlightAware) along two distinct flight corridors

3. Vehicle Swarms

The second and most complex strategy to plan and negotiate deconflicted trajectories is by implementation of swarming functions, for which parallels with present day operations can be drawn. A “swarm” is most generally characterized by the participation of two or more vehicles operating autonomously to coordinate their actions with the intent of achieving common goals [16]. In the context of this discussion, swarming between multiple vehicles could be applied to numerous situations such as surveying, firefighting, or search and rescue operations. In a more general sense, swarm control could be applied as a traffic management technique around airports and along airways.

There are multiple paradigms by which swarms may coordinate their actions. While IFR traffic delegates authority over its trajectory to ATC through centralized control, VFR aircraft transitioning to and from uncontrolled fields retain this control. By following right-of-way rules and coordinating actions by voice over radio, VFR pilots coordinate their actions by consensus. To operate cooperatively in the VFR and IFR environments, uncrewed aircraft would have to be capable of performing the same interactions with crewed and uncrewed aircraft, and ATC. An alternative method of coordination, by hierarchy, is implemented by Boeing’s Airpower Teaming System, in which orders from a controlling aircraft (F/A-18 or Poseidon) issue objectives to uncrewed combat aerial vehicles, that then execute and relay results to the controlling aircraft.

Hierarchical coordination is also implemented today in special mission scenarios such as firefighting. In this scenario, an “air attack” aircraft orbits the fire at 2500 ft AGL to coordinate actions between firefighting aircraft, which are either sequenced to the fire through vertically stacked holding patterns (Figure 22) to drop their loads, or follow a lead aircraft to their designated drop zones. An evolution of this system could comprise of a crewed air attack aircraft directing autonomous vehicles through the holding patterns, or a crewed firefighting aircraft trailing an autonomous lead aircraft which safely designates the best trajectory to a defined drop zone. Three advantages of studying the firefighting scenario are that firefighting operations take place in Temporary Flight Restrictions (TFR) (which imply the airspace is clear of other aircraft); the aircraft are often in the Restricted category which relaxes the regulatory burden; and operations are almost invariably over unpopulated areas.

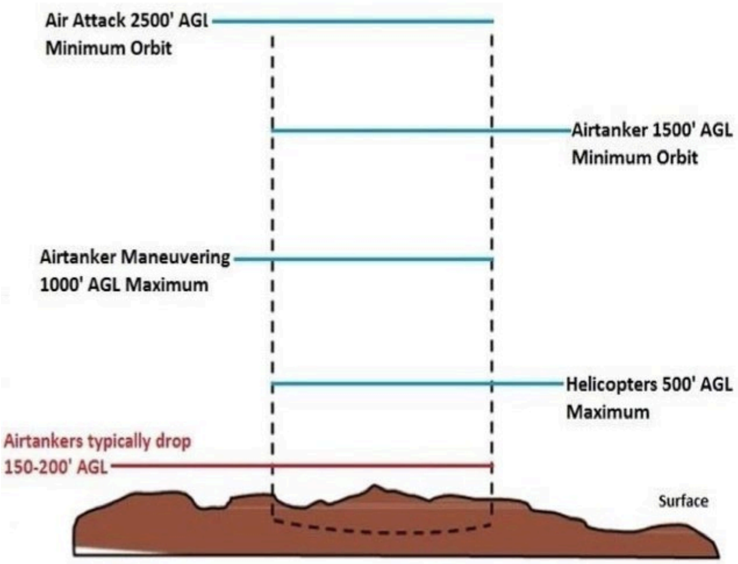


Figure 22: Fire Traffic Area, as flown by CalFire crews over wildfires [31]

4. Emergent behavior

One characteristic of coordinated vehicle interactions is emergent behavior. Idris [18] describes a study where multiple aircraft are tasked with crossing an area while avoiding prohibited areas and meeting an RTA constraint. In the simulation, each aircraft aims to conserve trajectory "flexibility," defined by two metrics: robustness and adaptability. The former is defined by the ability to keep the trajectory unchanged in the presence of disturbances, while the latter by the ability to change the trajectory in the presence of disturbances. The results of the study showed that implementing a trajectory flexibility-preservation algorithm has the effect of arranging the aircraft trajectories into structured patterns. For example, northbound and southbound trajectories naturally separated into two streams. A requirement however is that each aircraft communicates its trajectory to the others.

To enable collaborative behavior such as discussed above, vehicles must be able to communicate with each other to coordinate their interactions. This may be by direct communication (e.g., via datalink) or, for resilience in the case of communications failure, by flightpath observation and modeling. In the enroute airspace, a limited amount of intent data (i.e., the next two waypoints) has been shown to significantly reduce occurrences of loss of separation [28].

Paths Analysis

This section continues the discussions presented previously, but arranges the elements into implementation paths. The four paths presented below are meant to exemplify how the method described above may be applied. Paths to vehicle autonomy are highly complex, multi-dimensional, and context dependent. The objective of the following analyses is to illustrate the implementation of the structured path development method introduced in the previous sections. The intent is not to present the sample paths as definitive for the selected use cases, so the paths below should not be taken as *the* paths to autonomy, but as starting points to feed future discussions regarding the implementation of autonomy. The paths do not address the airworthiness certification aspects because these depend entirely on the specific implementations. Instead, the general airworthiness recommendations summarized in the Airworthiness Certification Mitigating Strategies Section should be observed. The paths are based on an analysis of current operational realities, and survey current industry and academic research efforts. These observations are used to steer the directions in which paths could go to maximize their chance of successfully enabling a business case.

The environment of each selected use case lends itself well to testing a subset of the core function superset. For example, firefighting aircraft are often operated close to the ground in austere environments. Therefore, the firefighting mission may prove to be fertile ground for developing autonomous capability margin assessment functions. This however does not mean that the crew must be responsible for all the other functions. For instance, trajectory management, which is also discussed in the context of aerial firefighting, requires conflict management. To manage conflicts, the DMS must have knowledge of them. Those conflicts may be defined by autonomous D-SA functions, or by the crew through Human Automation Teaming (HAT).

The paths shown in Figure 8 are cumulative in that they build upon each other by individually focusing on a specific functional aspect of autonomy. The first path, Part 135 inter-urban cargo, emphasizes DFV and D-SA functions. The second path, aerial firefighting, emphasizes capability margin assessment, vehicle awareness, and trajectory management functions. The third path, Part 121 SPO, emphasizes communications and mission management functions. The fourth and final path discusses all the functions in the context of UAM and relies on lessons learned through the three previous ones. This allocation of functions is represented in Figure 23.

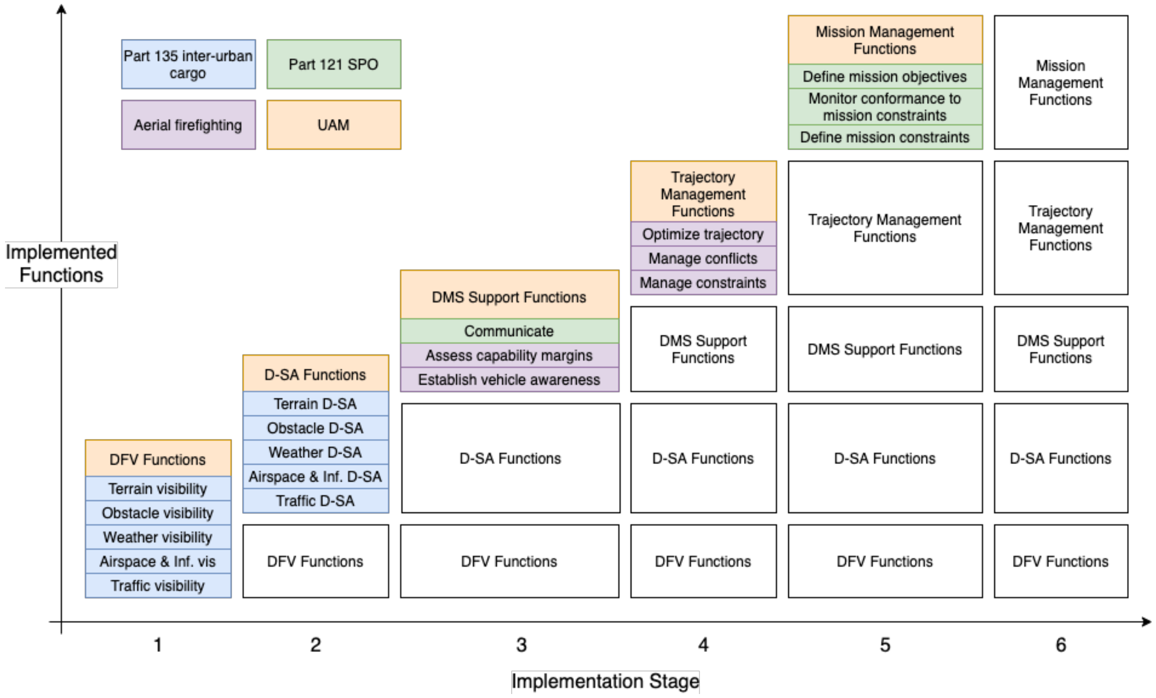


Figure 23: Each path focuses on a specific subset of functions. This does not imply that no other functions can or should be automated, only that each use case provides specific opportunities to test specific functions.

Path 1: Inter-Urban Cargo

Step 1: Use Case Identification

NASA's Regional Air Mobility (RAM) document [19] provides an in depth discussion on how airports in the USA can be better utilized to connect communities "point-to-point", a divergence from the traditional "hub-and-spoke" model implemented today by major airlines. The authors list barriers to RAM and provide motivating arguments to overcome them, such as to relieve traffic at capacity constrained airports. The document points out that advances in technology and implementation of new operational models could reduce hourly operating costs and noise for example, which are requirements for RAM. The document singles out autonomous capabilities as a requirement.

To jumpstart RAM, the focus is set on inter-urban air cargo because it is a low risk alternative to test technologies and procedures that may be required for RAM. Cargo operators such as United Parcel Service (UPS) have seen the need for their service increase in the past years, and UPS has expressed interest in expanding services to small communities by utilizing small novel aircraft of the likes of Beta Technologies [32]. Cargo operations in rural areas make up the use case for this path, since they represent a relatively low risk scenario to test new DFR operations and the novel autonomous technologies required to reduce aircraft operating costs – all RAM requirements. The use case is based on Federal Express route between Four Corners Regional (KFMN) and Gallup (KGUP), operated by Empire Airlines in a Cessna C208. (source: FlightAware, C208 registration N850FE). Appendix G: KFMN – KGUP Flight and Appendix H: KFMN – KGUP typical flight (Empire Airlines) show typical flight profiles.

Step 2: Airspace and Regulations

All airport and airspace information are found on airnav.com and skyvector.com, respectively.

Airspace

The following points define the airspace at between FMN and GUP:

1. The overlying airspace at FMN is Class D, with an operating control tower between 0600-2200 Coordinated Universal Time (UTC). Between 0600 and 2200UTC, radio communications and clearances to enter the airspace are required (14 CFR §91.129). Outside of these times, the airspace reverts to Class G and there is no communication requirement (14 CFR §91.126).
2. KGUP is an uncontrolled Class E airport with no requirement to communicate (14 CFR §91.127).
3. Both KFMN and KGUP have common traffic advisory frequencies to self-announce intentions when there is no active ATC.
4. The airspace between KFMN and KGUP, and outside of KFMN's airspace is Class E up to 18000 ft MSL.
5. The terrain between KFMN and KGUP is desertic and relatively flat, but rises from 5507ft at KFMN to 6657ft at KGUP.
6. KGUP has two GPS approaches (not WAAS LPV), and KFMN has four GPS (WAAS LPV) approaches.

7. New Mexico is mostly sunny throughout the year.

Regulations

The following points address relevant operations regulations:

1. 14 CFR §135.99(a) states that "No certificate holder may operate an aircraft with less than the minimum flight crew specified in the aircraft operating limitations or the Aircraft Flight Manual for that aircraft and required by this part for the kind of operation being conducted."
2. 14 CFR §135.99(b) states that "No certificate holder may operate an aircraft without a second in command if that aircraft has a passenger seating configuration, excluding any pilot seat, of ten seats or more."
3. 14 CFR §135.101 states that a second-in-command is required for passenger carrying operations under IFR, and 14 CFR §135.111 for Category II operations[1].
4. 14 CFR §135.105 states that "unless two pilots are required […] for operations under VFR, a person may operate an aircraft without a second in command, if it is equipped with an operative approved autopilot system."
5. There is no requirement to operate IFR at and between FMN and GUP. Therefore, outside of KFMN tower operating hours, there is requirement to communicate.
6. For revenue operations, the flight must be operated under Part 135. However, for non-revenue operations, the flight is operated under Part 91 which places no restrictions on crew requirements other than an aircraft must be operated by the minimum required flight crew specified in the aircraft operating limitations or the Aircraft Flight Manual.
7. 14 CFR §91.305 states "No person may flight test an aircraft except over open water, or sparsely populated areas, having light air traffic."
8. 14 CFR §91.319 states "No person may operate an aircraft that is issued an experimental certificate under §21.191(i) of this chapter for compensation or hire."

As indicated in the Airworthiness Certification section, applicants could petition for exemptions to any of these regulations, although some are unlikely to be relaxed in the short term.

Step 3: Functions Layering

Digital Flight Visibility and Digital Situational Awareness functions are the focus of this path since they are fundamental to DFR. Step 2 describes a simple environment which simplifies the problem of "visibility" by reducing the number of variables to detect and be aware of. This is useful in the short-term because initial tests would undoubtfully require the supervision of the crew. The DFV functions listed in Appendix E: Digital Flight Visibility must be implemented before D-SA functions listed in Appendix D: Digital Situational Awareness (D-SA) Functions, because the former is a pre-requisite of the latter.

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[1] A type of low ceiling and visibility approach. Special equipment and pilot training is required for approval from the FAA to execute Category II ILS operations.

Two repeated functions in the D-SA function set are to define conflicts and constraints. The underlying assumption of these two functions is that the aircraft has the ability to evaluate its capabilities and capability margins. For example, terrain awareness is not simply knowing where mountains are located. In an emergency landing scenario, it requires the system to analyze the locations of water bodies and topographical features to find the most suitable forced landing area given the vehicle's capabilities, if required. These kinds of problems which require "awareness" of a situation are less obvious to solve than the data collection required by DFV. In the short term, conflict and constraint definition remains the responsibility of the crew. However, vehicle capabilities assessment can be implemented as a parallel activity to DFV by post-processing relevant data that has been collected in flight. Machine Learning (ML) may be applied to learn vehicle performance as a function of environmental factors and system health, which goes hand in hand with the data collection activity of DFV. The advantage of using machine learning techniques is that the vehicle should be capable of extrapolating knowledge of capabilities to new situations, as a way to replacement human experience and intuition, which cannot be accomplished using standard performance data alone.

In addition to the functions mentioned above, companies such as Reliable Robotics and XWing have made great strides in implementing autonomy in the Cessna Caravan. Though details on their work are not in the public domain, the available information indicates that certain Vehicle Awareness functions (e.g., Vehicle Health, Systems Management, Guidance & Control) and DFV functions (e.g., traffic awareness) have been automated for nominal operations, which make the XWing and Reliable Robotics platforms ideal starting points. It is unclear how they address the challenge of communicating with other aircraft over radio, how they intend to operate cooperatively at uncontrolled fields, or how they approach off-nominal situations. The environment described in step 2 is an ideal low-risk space to test these new technologies.

Step 4: Technologies Analysis

As previously stated in step 3, XWing and Reliable Robotics have developed an ideal technological starting point for testing autonomous Vehicle Awareness functions in the Caravan. Thus far, emphasis has been placed on the C208 because the use case is contextualized through a FedEx mission. However, the environment proposed does not depend on the C208, and DFV functions can be tested in any aircraft in that environment. In addition, technologies that enable cooperative use of airspace in ADS-B and communication-deprived environments are required. This poses a challenge for DFV because a significant data source (ADS-B) cannot always be relied on for 100% traffic picture. Vision systems developed by Deadalean, for example, address this issue by using vision cameras [34], but how these systems work in IFR where there is limited to no visual visibility is unclear. The impact on DFV of sensor limitations must be evaluated, and sensor/data source combinations tested so that performance-based standards regulating Digital Flight Visibility can be written based on experimental data.

Another significant technological challenge is voice communication. Radio transmissions are not always intelligible or made in standard phraseology. For operating in areas with no air traffic control, the autonomous system will eventually have to be capable of transmitting intentions by voice over radio. The vehicle must, at a minimum, detect traffic and make radio calls that are consistent with the current air traffic situation (e.g.: not cut-off someone off on final approach;

avoid “stepping-on” another aircraft’s transmissions; follow right-of-way rules). In the short-term, this remains the task of the pilot.

The alternative is to implement a similar mandate to ADS-B, where all aircraft are equipped with instrumentation to receive text transmissions from autonomous vehicles. In the medium-term, autonomous aircraft will be required to not only transmit, but listen and “understand” such transmissions. Until this is achieved, the Caravan mission would be constrained to areas that do not require voice communications. These could include low-density area operations, or operations in controlled environments (where ATC is responsible for traffic spacing) using CPDLC to exchange text data with ATC. Operations at fields such as GUP and FMN provide an initial low-risk, low-density, sandbox to develop the procedures and technologies that fulfill these requirements, while gaining valuable operational experience. This also fulfills the data-mining imperative identified in the Airworthiness Certification Mitigating Strategies section.

Two additional technical development opportunities are electrification and DOAR operations. magniX has had recent successes in electrifying the DHC-2 Beaver [35] and the C208 [36]. Again, this environment lends itself to further testing of electric technologies in an operational context. Flight sectors are relatively short (~150 miles), and they overlay what is essentially a 150-mile-long runway, as the desert is full of landing options. Operating in this environment presents the opportunity to initially develop the Available Power Profile concept for electric aircraft along an “A to B” route, a key component of capability margins assessment. Key metrics can be obtained while a human-machine interface to convey the relevant data is developed based on experience gained through this use case. The typical flight profile shown in Appendix H: KFMN – KGUP typical flight (Empire Airlines) includes an initial climb to 3700m (12000 ft). DOAR clearance and navigation procedures can be tested while flying in VFR conditions in a sparsely occupied volume of airspace. At the same time, enabling technologies such as path optimization, and weather and traffic avoidance algorithms can be demonstrated, and sufficient data collected to establish the design assurance levels required for certification as discussed in the Airworthiness Certification section on page 36.

Path 2: Special Mission – Aerial Firefighting

Step 1: Use Case Identification

2020 was an exceptionally dry year for California, leading to California’s largest wildfire ever recorded. The August Complex fire burned over 1 million acres, an area larger than the state of Rhode Island [45]. Also exceptionally dry, Australia experienced one of its largest fires at 1.5 million acres. Over the years, California’s fire season has gradually lengthened as the state experiences prolonged periods of extreme drought. Large fires gather much attention, but the number of individual fires has also increased significantly, stretching firefighting crews thin across the state.

A significant resource in wildfire suppression are aircraft. Firefighting aircraft are usually restricted to daytime operations due to the high risks associated with operating low level in mountainous regions, around other aircraft, and over fires. Night-time operations would not only allow aircraft to operate continuously, but would also enable firefighting during times when wind speeds and temperatures are typically lower and humidity levels higher. In other words, fighting fires at night could be more effective than during the day. A solution to reduce the risk is by introducing automation for tasks such as terrain-following and aircraft control, freeing the pilot to focus on mission management and coordination with other aircraft. Therefore, the use case for this path comprises day and night firefighting operations in remote mountainous areas. The firefighting mission is convenient because it is a self-contained use case in which a higher level of risk is tolerated.

Step 2: Airspace & Regulations

1. Temporary Flight Restrictions in wildfire areas prohibit all non-participating aircraft to enter the delimited zone.
2. Regions near wildfire are often evacuated of all inhabitants
3. Firefighting aircraft operate in a structured airspace of vertically stacked orbits (Figure 22) under the direction of an air attack aircraft at the top of the stack
4. Large air tankers (B747/DC-10) may follow smaller lead aircraft for directions to their drop zones.
5. 14 CFR §21.25 (1) specifies that aircraft must meet “the airworthiness requirements of an aircraft category except those requirements that the FAA finds inappropriate for the special purpose for which the aircraft is to be used”
6. FAA Order 8110.56B states that the “FAA can waive or modify basic airworthiness requirements that are found inappropriate, provided the level of safety for the public is maintained through additional operating restrictions imposed via 14 CFR 91.313”
7. 14 CFR §91.313(e) states that “no person may operate a restricted category civil aircraft within the United States (1) Over a densely populated area; (2) In a congested airway; (3) Near a busy airport where passenger transport operations are conducted”
8. The combination of location and airspace restrictions around fires is conducive to compliance to minimum restricted category requirements.
9. 14 CFR §91.815 sets a precedent for the FAA making operational exceptions for firefighting aircraft.

As before, applicants could petition for exemptions to any of these regulations.

Step 3: Functions Layering

Vehicle Awareness and Digital Flight Visibility functions are addressed in Path 1, and they are actively being developed by industry. The environment particular to firefighting provides the opportunity to develop capability margin and vehicle awareness functions. Simultaneously, firefighting procedures provide the opportunity to develop trajectory management functions. Because of the high diversity of vehicles and coordination with local officials and ground crews, in the medium term, firefighting vehicles will likely rely on humans for mission management functions.

Since firefighting often takes place over difficult terrain and in difficult weather conditions, operations will benefit from robust vehicle awareness and capability margin assessment functions. For example, real time functions to determine aircraft performance or to autonomously control aircraft systems would likely increase safety and efficiency. Better performance predictions lead to more optimal trajectories, and autonomous control frees the crew to focus on mission management.

While vehicle awareness and capabilities assessment functions are developed, trajectory management functions can be developed by instituting “follow-the-leader” algorithms. In this scenario, either the lead or tanker aircraft is autonomous and receives an order to lead or follow, respectively. It is assumed that one of the two vehicles is crewed because the autonomous vehicle is not readily capable of mission management functions. In addition to terrain, obstacles and local weather visibility, leader and follower vehicles must be able to formate on each other. Ideally, the leader aircraft has a representation of the capabilities of the follower aircraft to not lead it on a trajectory it cannot follow. In the case where the leader aircraft is autonomous, it must be able to either receive a destination to lead the follower to, or have functions to determine the best area for the follower to drop its load. Based on a desired drop zone and formation point, the leader aircraft then plots a flyable trajectory.

Trajectory management functions may also be developed through vehicle swarming algorithms. The Fire Traffic Area (FTA) shown in Figure 22 is composed of vertically stacked holding patterns in which aircraft can autonomously and cooperatively self-organize. This airspace structure separates aircraft of different types with different capabilities, and organizes air traffic. As an aircraft is cleared by the air attack aircraft to drop its load, it exits the lowest holding pattern in the FTA, and all aircraft above may descend to the next lowest available holding pattern. This traffic management mechanism can be beneficially automated to significantly increase safety by reducing the manned aircraft exposure to the fire risk. In such a scenario, the orbiting aircraft would autonomously manage their trajectories in the FTA while remaining aware of other traffic, smoke and obstacles based on information gathered by DFV functions Lessons learned from applying these functions in this austere environment will help develop concepts such as SATS HVO for use at conventional fields and UAM vertiports.

Step 4: Technologies Analysis

Erickson and Sikorsky have announced intentions to retrofit the S64 Air Crane firefighting helicopter with Sikorsky’s MATRIX technology [46] , which enables pilots to focus more attention on mission management tasks and less attention on flying the aircraft. This technology provides an initial starting point for implementing vehicle awareness and capabilities assessment in the firefighting environment, and enables remotely controlling the vehicle from a distance by providing it mission objectives. To support the swarming functions, vehicle-to-vehicle communication technologies must be developed, though in the short term crews could be responsible of performing this function. IEEE working group P1920.2 is developing a standard that defines data exchange protocols between UAV’s. In addition, trajectory management technologies are required.

Combining technologies like MATRIX with communications technologies (which still need to be developed), the remaining gaps are mainly in software development and operations, which rely on the same technologies discussed in Path 1. The advantage of Path 2 is that such operations are inherently more tolerant to risk because of the danger posed by the environment. In addition, extra measures are taken to mitigate the risk to civilians and non-participating aircraft which provides an additional measure of protection.

Path 3: Single Pilot Airline Operations (Part 121)

Step 1: Use Case Identification

According to Boeing’s 2020-2039 Pilot and Technician Outlook [41], by the year 2039 the world will need 605,000 qualified airline pilots to keep up with air travel demand, exceeding the rate at which pilots are currently trained. Given these numbers, the motivation for finding solutions to the pilot shortage is clear: means must be developed to increase qualification rates and to develop technical solutions to reduce crew-number requirements. Cargo operators have expressed interest in developing technologies to reduce the Part 121 required-crew from two to one pilot (14 CFR §121.385(c)), as evidenced by the FedEx/Sikorsky ATR42 (two crewed, Part 25 aircraft) project currently underway [39].

This path examines the implementation of single-pilot scheduled cargo operation in a Part 121 environment between California and Hawaii, as shown in Figure 21. The use case assumes a twin turbine aircraft, equipped as per Part 121 requirements. As for Path 1, an oceanic setting (controlled by Oakland ARTCC in this case) has been selected because it constitutes a relatively low risk environment compared to overland flight over populated areas for several reasons:

1. Overwater flight in a non-radar environment necessarily has a lower traffic density than corresponding operations in a radar environment which covers most of the contiguous United States;
2. Terrain and obstacle considerations are generally not an issue for long-range overwater flights;
3. In the worst case, it is highly unlikely that third-party injuries or fatalities would arise if the aircraft were forced to ditch in the ocean;
4. The number of contingency options during long over water flights is significantly lower than for continental operations which facilitates the implementation of a robust decision-making system; and
5. In the case of a pilot incapacity, the trajectory management and ATC considerations are considerably simplified because of the lack of high density airspace and busy airports in oceanic areas. Because of the distances involved, it is also likely that there would be ample time to prepare the destination airport for an emergency automated landing.

Future Air Navigation System (FANS) requirements which apply in this space reduce the amount of data uncertainty by requiring ADS-C and CPDLC.

Step 2: Airspace & Regulations

1. Oakland oceanic airspace supports FANS 1/A CPDLC and ADS-C capabilities
2. Traffic density is cyclic with highs during the day, and lows at night.
3. 14 CFR §121.385(c) requires that there be at least two pilots on board.
4. 14 CFR §121.163(a) states that “No person may operate an airplane not before proven for use in a kind of operation under this part [121] or part 135 of this chapter unless an airplane of that type has had, in addition to the airplane certification tests, at least 100

hours of proving tests acceptable to the Administrator, including a representative number of flights into en-route airports."

5. 14 CFR §121.163(e) states that "No certificate holder may carry passengers in an aircraft during proving tests, except for those needed to make the test and those designated by the Administrator. However, it may carry mail, express, or other cargo, when approved."
6. 14 CFR §121.354 states that "No person may operate a turbine-powered airplane unless that airplane is equipped with an approved terrain awareness and warning system."
7. 14 CFR §121.356 states that effective January 1, 2005, any airplane operated under Part 121 must be equipped with TCAS.
8. 14 CFR §121.357 states that "No person may operate any transport category airplane (except C-46 type airplanes) or a nontransport category airplane certificated after December 31, 1964, unless approved airborne weather radar equipment has been installed in the airplane."
9. 14 CFR §121.358 states that "No person may operate a turbine-powered airplane manufactured after January 2, 1991, unless it is equipped with either an approved airborne windshear warning and flight guidance system, an approved airborne detection and avoidance system, or an approved combination of these systems."

Once again, applicants could petition for exemptions to any of these regulations.

Step 3: Functions Layering

Successful implementation of SPO will require a combination of technical and operational solutions to address four combinations of operational scenarios, in order of increasing complexity:

1. Normal operations with a functional pilot
2. Non-normal operations with a functional pilot
3. Normal operations with an incapacitated pilot
4. Non-normal operations with an incapacitated pilot

The first and second combination hinges on the implementation of decision support tools and changes to regulations specifically prohibiting SPO, such as 14 CFR §121.385(c). There already exist a number of high-performance Part 23 aircraft such as the Phenom 300 or the Piaggio P180 Avanti certified under Part 23, capable of operating in the same environment as large Part 25 airliners. The systems of these aircraft are often more complex than their highly automated modern Part 25 counterparts, and there is nothing intrinsically more difficult about large transport SPO operations than those for the general aviation types that are already SPO-capable. Pilots of these aircraft are increasingly performing monitoring and mission management functions.

Under normal operations with an incapacitated pilot, the vehicle must autonomously perform pilot health assessment functions to determine if the pilot is incapacitated, including fatigue and low levels of engagement. These functions could work by occasionally querying the pilot for a response and by applying behavior models. Based on these assessments, the vehicle may choose in real-time what tasks to allocate to the pilot, depending on how alert and engaged the pilot is.

For example, in situations where the pilot is fatigued, the system may choose to conduct high workload tasks such as landing.

There are several potential strategies to cover the corner case where a pilot may be completely unresponsive. The first is to train the loadmaster (or flight attendants for passenger carrying operations) to respond to the situation by providing them basic training. Garmin's Autonomì™ technology goes one step further and only requires the push of a button for the system to find the nearest suitable field and land there autonomously. This strategy requires the aircraft to be functionally *and* operationally autonomous. The third strategy involves remotely controlling the aircraft from a ground station. Regardless of the adopted strategy, the mission objective becomes safely landing the aircraft.

Non-normal operations with an incapacitated pilot represent the most complex situation and will likely require AI functions to learn the degraded aircraft performance. Novel operational procedures will likely be required as well. An example similar to ETOPS would require SPO aircraft to remain within a certain flight time from designated fields (such as Edwards Air Force Base with its extensive lake-bed runway complex) outside of densely populated urban centers. Additionally, autonomous decision-making functions will be required. An aircraft with a partially extended landing gear and an incapacitated pilot will need functions to determine the most favorable landing site, actions to attempt to completely lower the gear, what to communicate to what agency, etc.

Despite particular functional requirements for each combination, the core functional requirements are the same for combinations 1, 2, 3 and 4; the difference is in which entity is responsible for their execution, the determination of which will likely be an iterative process. Table 5 allocates function execution responsibility to the pilot or the automation based on worst case scenarios. Following this approach, an incapacitated pilot is completely unconscious and cannot be relied on even for the simplest tasks, such as pressing a button. Similarly, in non-normal operations the aircraft has no autonomous ability. The arrows represent the fact that the reality is more nuanced. For instance, in non-normal operations with a functional pilot, not all systems will necessarily have failed, and so the responsibility of executing vehicle awareness functions may be shared between the pilot and the automation.

This approach highlights the difficulty of the non-normal operations, incapacitated pilot case. By process of elimination, an unconscious pilot cannot have any functions execution responsibility, subsequently placing the onus for function execution on the vehicle. For this to be viable, highly reliable, resilient, and redundant systems need to be developed to maintain a minimum level of required functionality to land the aircraft safely.

Table 5: Functions allocation matrix

Combination	Pilot	Automation
Normal Operations, Functional Pilot	Mission Management, Trajectory Management, D-SA	Vehicle Awareness, DFV
Non-normal Operations, Functional Pilot	Mission Management, Trajectory Management, D-SA, Visibility, Vehicle Awareness	→
Normal Operations, Incapacitated Pilot	←	Mission Management, Trajectory Management, DFV, D-SA, Vehicle Awareness
Non-normal Operations, Incapacitated Pilot	←	Mission Management, Trajectory Management, DFV, D-SA, Vehicle Awareness

Step 4: Technologies Analysis

Sikorsky has begun automating S76 and UH-60A helicopters with their MATRIX software [38], which enables pilots to focus more attention on mission management tasks and less attention on flying the aircraft. Similarly, Airbus' Automatic Taxi, Takeoff and Landing (ATTOL) was developed to help pilots focus more on "strategic decision-making and mission management" [42] by automating high workload flight phases. Combining such technologies with automated systems management will effectively enable the pilot to focus on decision-making and planning.

Technologies such as Garmin's Autonomì™ have started to address the requirement for systems that can take over the mission planning functions if the pilot is incapacitated. For such systems to be implemented in the structured flight levels environment, they must become "cooperative." FANS 1/A equipage requirements include CPDLC and ADS-C, two communication technologies that enable text controller-pilot communications and automated position reports, respectively. The implementation of text communications simplifies the communication challenges posed by voice communications and defines an unambiguous, traceable method of exchanging information. The CPDLC message set is large and includes negotiation queries and requests [40]. In addition, ADS-C provides ATC with current state, intent and meteorological data [40].

Vehicle-to-vehicle communication is a technological requirement for the expansion of DOAR operations in the flight levels. By implementing vehicle-to-vehicle CPDLC and ADS-C technologies, aircraft could communicate with each other to cooperatively deconflict trajectories without ATC communications. Because ADS-C is capable of transmitting flight plan intent data, aircraft could be aware of other trajectories being flown around them. Similarly, weather reports could be shared between aircraft through automated queries or upon pilot request. Supporting avionics interfaces and procedures will have to be developed. To assist pilots in their mission management functions, TASAR and ASTAR technologies deployed in the environment described in step 2 serve as ideal starting points for studying the implementation of RTA and FIM applications for flight profiles like the one shown in Figure 21. In situations where FIM is not appropriate, NASA's AOP pattern-based genetic algorithm could be tested.

Technologies capable of executing the performance learning functions are required. McCrink et al. have developed machine learning algorithms in a sUAS platform [43] capable of learning how to fly an airplane in real time, without prior knowledge. This is particularly important for covering abnormal situations that could not be foreseen, and for which pilots' response currently relies on instinct and experience. Lastly, autonomous decision-making systems will also be required. Ontologies have been used to supply expert systems with the knowledge base to execute procedures and D-SA required for decision making [44]. Machine learning algorithms will be required to add resilience to deterministic expert systems, which are brittle when faced with situations for which there is no prescribed outcome.

Path 4: High Density Urban Air Mobility

Step 1: Use Case Identification

Uber's 2016 white paper provides an in-depth analysis of motivations for UAM which will not be repeated here. This use case for this path considers an autonomous aircraft connecting two points at opposite ends of San Francisco, as shown in Appendix I: UAM Use Case Trajectory. For illustrative purposes, the flight originates in San Jose, and terminates in San Francisco's financial district, but the use case is not limited to this airport pairing.

Step 2: Airspace & Regulations

1. The trajectory flies mostly over water.
2. The flight originates from within the core of San Jose's class C airspace and crosses through Moffet and Palo Alto class D airspace, and the core of San Francisco's class B airspace.
3. At 1000 ft AGL, the aircraft remains clear of controlled airspace except for those areas mentioned in point 2.
4. 14 CFR §91.129, §91.130 and §91.131 require aircraft to receive a clearance and maintain two-way radio communication with ATC in class B, C and D airspace
5. 14 CFR §91.111(c) states that "No person may operate an aircraft, carrying passengers for hire, in formation flight."
6. 14 CFR §91.119(b) states that no person may operate an aircraft "Over any congested area of a city, town, or settlement, or over any open air assembly of persons, an altitude of 1,000 feet above the highest obstacle within a horizontal radius of 2,000 feet of the aircraft."
7. 14 CFR §91.119(d)(1) states that "A helicopter may be operated at less than the minimums prescribed in paragraph (b) or (c) of this section, provided each person operating the helicopter complies with any routes or altitudes specifically prescribed for helicopters by the FAA."
8. The Aeronautical Information Manual (AIM) defines VFR corridors as "airspace through Class B airspace, with defined vertical and lateral boundaries, in which aircraft may

operate without an ATC clearance or communication with air traffic control." (Section 3-5-7).

9. Special Flight Rules Areas (SFRA) specify areas where certain regulations do not apply. For example, 14 CFR §93.97 states that aircraft within the Los Angeles SFRA are not required to communicate with ATC.
10. 14 CFR §107.51 specifies that small Unmanned Aircraft System (sUAS) must be operated below 400 ft AGL unless they are operated within 400 ft of a structure.

As for the other three use cases, applicants could petition for exemptions to any of these regulations.

Step 3 & 4: Functions Layering & Technologies Analysis

The functions and technologies required for high density UAM are a combination of those presented in paths 1, 2 and 3.

A candidate solution for implementing automation in high density urban areas is to begin small (e.g., < 25 kg) UAS drone operations in the UAM environment. Small UAS operations are already being performed and are potentially a lower risk alternative to test new procedures and technologies in the 400 – 1000 ft range. However, the following Part 107 rules must change for such operations in urban areas:

1. 14 CFR § 107.41 prohibits flights in class B, C, D, E without authorization from ATC.
2. 14 CFR § 107.12 requires a remote pilot.
3. 14 CFR § 107.52 prohibits flight with a transponder. 14 CFR §91.215 requires a transponder to operate in class B and C.
4. 14 CFR § 107.31 requires that the remote pilot maintain visual line of sight.
5. 14 CFR § 107.35 prohibits a pilot from piloting more than one aircraft at a time.

Delivery UAS operations along prescribed routes is coming in the short-term. NASA and Longbow have recently announced their intent to pursue this project in Virginia [50]. Lessons learned will enable a transition to passenger carrying UAM.

An initial step is to define new airspace boundaries in urban areas for UAM operations. Due to part 91 and 107 regulations, altitudes between 400 and 1000 can be considered "empty" of cruising traffic. Additional provisions must be made for traffic departing and arriving at airports which has already been discussed [47]. Geofencing functions are required to ensure that vehicles do not inadvertently enter these protected approach and departure paths under 1000 ft. Helicopters and light aircraft could then be used to transition from small UAS to larger vehicles to test the newly developed procedures, and the FAA would help produce regulations under which such vehicles could operate. In the short-term, concise routes along pre-approved corridors in crewed non-passenger carrying aircraft is the likeliest initial scenario. Such operations would allow the testing and development of required technologies, such as the electrification developed in path 1, while helping identify any technical, functional, and operational gaps.

The advantage of beginning urban operations with corridors is that it simplifies the trajectory management task and isolates UAM aircraft from other crewed non-UAM traffic. Corridors can be placed over more sparsely populated areas, in close proximity to emergency landing areas, or over areas less sensitive to noise. They also have the advantage of creating a boundary with crewed aircraft which may not be able to communicate and deconflict trajectories with autonomous aircraft. This directly lowers the risk of urban operations. Although corridors will initially limit the airspace volume in which vehicles will be allowed to operate, they should be wide enough to allow trajectory deconfliction technologies to prove themselves. In other words, a corridor should not be a line all aircraft must travel on, but should be a tunnel in which aircraft can travel through. A direct analogue are highways, which are not so narrow that cars are restricted to following each other in one lane, but are bounded by guardrails that limit the space in which drivers may travel and pass each other. The dimension of corridors will be experimentally determined, and is likely to be a function of navigational precision, the number of vehicles traveling within it, the surrounding airspace, and the location of noise sensitive areas. Once technologies have proven themselves and the issue of communication with other aircraft has been resolved, the natural next step is to eliminate the corridors and transition to “free flight”.

Because of the altitude range proposed, vehicles must have methods to find suitable places to land in emergency situations. Conventional aircraft can glide or autorotate in the event of engine failure, and some of the designs being proposed by industry clearly lack these capabilities, as noted in EASA SC-VTOL-01. Ballistic parachutes issued under a Special Condition could provide a short-term solution, while novel airframes and autonomous decision-making systems prove themselves. While Cirrus recommends that from straight and level its parachute system be deployed between 400 and 600 ft [48], a solution is required for deploying parachutes from a much lower altitude (e.g., while a vehicle is descending to a vertiport). ASR has been developing a parachute system capable of deploying much more rapidly [49]. However, in the long-term, UAM vehicles will be required to execute functions to find the nearest and most suitable emergency landing zones and must demonstrate the robustness and reliability to achieve them under all foreseeable failure conditions.

Vehicle-to-vehicle communication is a fundamental enabler of high-density operations of electric vehicles. To alleviate reliance on centralized control, trajectory intent data must be shared directly between vehicles for deconfliction. Lessons learned from DFR operations in path 1 and V2V communications in path 3 will inform technological requirements for the UAM environment. Information describing the available power profile, capabilities, and visibility may be required to redefine todays simplistic right-of-way rules to better-suit the technical constraints of electric vehicles. Different trajectory deconfliction strategies could be applied depending on density, but all rely on vehicles “handshaking” with their intents:

1. Low density: vehicle-to-vehicle negotiation prioritized by energy margin, capabilities margin, and DFV. FAA PSU may be used as communication nodes, but the decision-making remains on-board the aircraft.
2. Medium and High density: Aircraft comply with RTA constraints and synchronize flight paths by executing in-trail “leader-follower” and other swarming functions, as discussed in path 2. RTA constraints may be issued by PSUs. Structured vertiport airspace concepts

and procedures will be required to minimize loitering and hover times. Crewed aircraft will likely be required to be flown on autopilot, as is the case for RVSM operations today.

Aircraft that will also operate above 1000 ft AGL will have to comply with all normal VFR and IFR regulations. Above 1000 ft, RTA, in-trail and swarming will not be required since compliance to ATC instructions prevails. UAM aircraft therefore must have functions to accept, request, request-to-change, and deny ATC instructions. They must also have functions to convert instructions from text or voice into actionable tasks on-board. For example, if a UAM aircraft receives an instruction to climb and maintain 3000 ft and turn left to a heading of 150, it must have functionality to take this command and program its autopilot. The capability to receive an instruction in text form already exists with CPDLC, with the exception of the "execution" command, so this technological gap is not a large one. In all airspace, TCAS and ACAS-Xu (under development) would be retained as stand-alone tactical safety nets.

Conclusion

The analysis in this paper used a technology-agnostic approach to generate four sample "paths to autonomy" which considered the need for a viable business model, the resulting use case, airspace and regulatory considerations, functional allocations between the automation and the human pilot (if any), and the state of the technology. It should be emphasized that the approach used for this analysis effectively dissociates the technological challenges associated with crewless aircraft from the implementation challenges associated with operating autonomously.

The paths were built from a superset of "piloting" functions that must be performed by an autonomous vehicle, whether it is piloted or not. An ontology was introduced which imposes structure on this process and which could be expanded as the knowledge-base grows. In addition to providing an easily understandable representation of the functions, the ontology also plays a pivotal role in identifying gaps and unexpected functional interrelationships. Despite the extensive list of functions that was developed using this approach, the key element is the structure and methodology.

A critical distinction was made between *functional autonomy* (the own-ship technical capability to perform a function through control inputs and system management) and *operational autonomy* (the ability to operate safely and autonomously under the constraints imposed by the regulations and operating procedures through the automation of the decision-making function). Neither definition precludes crewed flight operations, but functional autonomy is a prerequisite for operational autonomy.

A number of emergent concepts arose from the functional analysis, some of which have been foreseen in the literature, and others that have not. These include:

Digital Flight Rules (DFR) – a set of operational guidelines that allow vehicle operators to assume full responsibility for traffic separation and trajectory management in all visibility conditions and airspace regions. DFR complement VFR and IFR and are compatible with them;

Digital Situational Awareness (DSA) – the system's knowledge of its own internal state (e.g., system health), as well as of external factors, such as weather, terrain, obstacles, traffic, and airspace and infrastructure;

Digital Flight Visibility (DFV) – the average time (or distance) horizon from the aircraft's present location, that a system in DFR operations can detect terrain, traffic, weather, and obstacles based on a combination of static (database), on-board real time (sensor) and external (data-link) data; and

Aircraft Capability Margins – a comparison of some aspect of available system capability (e.g., electrical duration remaining) in the context in which the capabilities are being evaluated (e.g., flight time to destination).

The functions derived from the preceding analysis were "exercised" through the development of four paths to autonomy. Diverse use cases were presented: an inter-urban cargo operation, a special mission fire-fighting aircraft, a single-pilot long-haul air carrier, and a high density UAM operation. Each use case built upon its predecessor, adding additional technical, operational, and certification challenges. The overall strategy that guides the path analysis lies in implementing change gradually, in stepped use cases which progress for low to high risk. Each path is rooted in a specific use case to motivate the adoption of autonomous functions and technologies, while identifying required regulatory changes.

Once again, the emphasis was on the four-step method proposed for the constructions of the paths. The method entailed a sequential analysis of the business case, airspace and certification considerations, functions, and technologies.

Adherence to this structured methodology has resulted in four incrementally deployable paths to autonomy that can be integrated into the existing airspace and procedural structures with the minimum of disruption.

Airworthiness regulations were examined, and the importance of a structured approach to the early identification of required rulemaking changes, special conditions, and exemptions was emphasized. This included the addition or changes to some of the definitions in 14 CFR § 1.1 which could be critical to the successful deployment of pilotless automation and AI.

The early implementation of formal programs to obtain quantified reliability and safety data for any new technologies or procedures was emphasized. Data mining will undoubtedly be of critical importance as a tool to aid in the certification of new technologies, particularly for non-deterministic functionality such as AI decision making.

Appendix A: Data System

An autonomous vehicle can derive information in three principal ways: through static databases, dynamically (e.g., via data-link), or through on-board real-time sensors. The following sections address each aspect of vehicle System and Situational Awareness, the relationships between these elements and the available data types.

Vehicle System Awareness Matrix

Vehicle System awareness is defined as the vehicle's internally-derived knowledge of its own systems status, Guidance & Control, and health functions as shown in Table 6.

Data Attributes		**Situational Awareness Elements**		
Data Classification	**Data Source**	**Systems Management**	**Guidance & Control**	**Vehicle Health**
Static (i.e., pre-composed)	**Database**	Aircraft performance tables	Control laws	System specs
Dynamic (e.g., datalink)	**Surface -> Air**			
	Air -> Surface Air <-> Air	ACARS reports		Broadcast
On-board (e.g., sensor-based)	**Ownship Sensors**	Powerplant Environmental Flight control Hydraulic Electrical	Air Data / GPS/ INS	RNP/ANP Performance Capabilities & margin Power profile

Table 6. Vehicle System Awareness elements.

Vehicle System Awareness - Vehicle Health

Vehicle health has two components: locally generated (sensor-based) health data, collected within the vehicle, and vehicle "health broadcasts" relayed to other vehicles or Air Traffic Management (ATM) agencies. Both components are linked in that the locally generated health data provides the vehicle with a depiction of its capabilities, while the broadcast enables it to provide external agents with information on those capabilities when required.

Vehicle Situational Awareness (SA) Matrix

Vehicle Situational Awareness is defined as the vehicle's knowledge of the terrain, weather, traffic, obstacles, and airspace & infrastructure. These SA factors can be derived statically (e.g., from databases), dynamically via data-link, or via on-board sensors as shown in Table 7.

Data Attributes		**Situational Awareness Elements**				
Data Classification	**Data Source**	**Terrain**	**Weather**	**Traffic**	**Obstacles**	**Airspace & Infrastructure**
Static (i.e., pre-composed)	**Database**	MEA/MOCA OROCA/MORA Min Quad/ Minima. Topographical Database			Buildings, Antennae, other permanent features	Airspace Boundaries, Runway information, Frequencies…
Dynamic (e.g., datalink)	**Surface -> Air**		FIS-B/ADS-B/ XM	ADS-B/TIS-B/ Intent Data	NOTAM	TFR/NOTAM
	Air -> Surface **Air <-> Air**		Turbulence/ Icing (growth) Temp/Wind Sensor Data	ADS-B/ADS-C Intent data Self-separation and Right-of-way Handshake		
On-board (e.g., sensor-based)	**Ownship Sensors**	LiDAR RADAR	Turbulence Icing Wind/Temp	RADAR (growth)	RADAR/LIDAR Active obstacle detection required below 400 ft	

Table 7. Situational awareness data sources and users.

Vehicle Situational Awareness – Terrain Awareness

Static Data

Altitude minima such as Minimum Enroute Altitudes (MEA), Minimum Obstacle Clearance Altitudes (MOCA), minimum quadrant altitudes and approach minimums are examples of the kind of data that inherently carry terrain data without observing specific terrain elevations. By respecting theses minimum altitudes, IFR pilots guarantee themselves terrain clearance without needing topographical maps, simplifying the terrain awareness task. The same concept could be applied to functionally autonomous aircraft.

On-board (Sensor-based) Data Generation

VFR flying requires a visual awareness of terrain to remain clear of it, and so the terrain data processed by pilots is infinitely more granular than the terrain data processed by IFR pilots. By flying visually and gathering terrain data in real-time, pilots are capable of flying lower to the ground, through mountain valleys for example. Certain functionally autonomous aircraft should have the same capability; crop dusting and firefighting are missions that require high resolution terrain awareness that cannot be replaced by adherence to published minimum altitudes. This terrain awareness can be achieved by combining LiDAR or RADAR technology and static topography databases. The combination of sensor and static data improves functional resilience in case of sensor failure and increases the Digital Flight Visibility (DFV). Conversely, functionally autonomous aircraft operating on published flight paths may not require this functionality since published flight paths are naturally kept clear of terrain. In the flight levels terrain awareness is maintained by static altitude minima data, and adherence to terminal procedures guarantees terrain clearance in the approach and departure.

Vehicle Situational Awareness – Weather Awareness

Dynamic Data

Weather is a highly dynamic environmental component that cannot be described by static data. To maintain weather awareness, external data sources compiled by ground infrastructure should be used such as FIS-B or XM data. These surface-to-air data packages provide a wealth of current and forecast weather information describing icing and turbulence conditions, winds aloft, airport conditions or convective activity. A complete listing of FIS-B data can be found here: https://www.faa.gov/nextgen/programs/adsb/pilot/#fisb

In addition, weather data is also crowdsourced by aircraft in air-to-surface communication links. This is done today by automated Air Reports (AIREPS) and Pilot Reports (PIREP). Pilot reports typically describe cloud tops, turbulence, icing or any other notable weather phenomena that could be hazardous. PIREPS are then disseminated to other aircraft via voice or through the FIS-B service and used to corroborate forecast data. Functionally autonomous aircraft should be expected to perform similar functions.

On-board (Sensor-based) Data Generation

In addition to using on-board sensors to record and share weather data with other airspace users, vehicles should be capable of comparing forecast weather with actual weather in real time to determine capability margins.

On-board weather sensors also increase the aircraft's DFV, the extent to which depends on the suite and range of the sensors. For example, weather RADAR, lightning detection, icing sensors, and turbulence detection systems provide the vehicle with real time awareness of weather phenomena. The reliability and range of these observations contribute directly to the vehicle's DFV.

What data the vehicle should be expected to have depends on the vehicle's mission. Crop dusting vehicles often perform short flights within a relatively small radius and so the weather awareness function could be delegated to an external operator. The operator would signal the presence of adverse weather to the aircraft to trigger an appropriate action. Firefighting vehicles also perform short flights within a relatively small radius, but operate around fires which generate smoke, and can be associated with fire tornados and microbursts. In this case, it may be more appropriate for the vehicle to rely on its sensors to have weather awareness functional autonomy since these short-lived environmental factors can be difficult to predict and track.

Vehicle Situational Awareness – Traffic Awareness

Dynamic Data

Traffic awareness can be divided into two subcategories: present state and future state. Present state traffic is obtained real time by air-to-air ADS-B and surface-to-air TIS-B data. These data are used to self-separate and to apply right-of-way (RoW) rules which will vary depending on the situation. If two aircraft have to deconflict their trajectories, they could apply basic RoW rules or time permitting, negotiate an alternative deconfliction strategy amongst themselves. The deconfliction negotiation should be supported by intent data such as those data disseminated by ADS-C. In this case, aircraft have information on where the conflicting traffic is, and where that traffic intends on going next. A direct air-to-air communication between the two aircraft should be available to facilitate real-time, decentralized and autonomous deconfliction. Communication standards and protocols should be established to support these exchanges. In the event that a conflict goes undetected until it is too late to negotiate or apply RoW rules, existing technologies such as TCAS are used as a failsafe. Similarly, if conflicting aircraft fail to establish a communication link between each other, basic RoW rules should be applied.

On-board (Sensor-based) Data Generation

At a minimum, aircraft should have the capability to gather traffic data with their on-board sensors such as ADS-B and RADAR. In the event of one sensor failure, the vehicle still retains traffic awareness through the other(s) sensor(s). If intent data becomes unavailable, then basic RoW rules should be applied.

The deconfliction procedures that are to be followed may vary depending on where the vehicle is operating and mission it is performing. Deconfliction procedures in dense UAM environments may require oversight or additional airspace structure to enable safe separation, which may differ from operationally autonomous aircraft operating in the flight levels. Regardless of the operating environments and missions, appropriate RoW rules and procedures should be established as guiding frameworks to simplify the deconfliction problem.

Vehicle Situational Awareness – Obstacles Awareness

Static Data

The FAA maintains the Digital Obstacle File (DOF) which documents known obstacles as defined by 14 CFR §77.17 “Obstruction standards.” Similarly, to terrain awareness, functionally autonomous aircraft operating on published flight paths may not require static obstacle data since published flight paths are inherently clear of obstacles.

Dynamic Data

Presently, the mechanism used to transmit data about transient obstacles is the Notice to Airmen (NOTAM) system. Among many other data, NOTAMS contain information about temporary obstacles such as cranes that cannot be published in permanent databases. Functionally autonomous aircraft should have access to NOTAMS to increase their obstacles awareness.

On-board (Sensor-based) Data Generation

Depending on the nature of the mission, functionally autonomous vehicles could be required to be capable of detecting obstacles in real-time by on-board sensors such as LiDAR or RADAR. For example, UAM vehicles operating low to the ground should be expected to look for obstacles in real-time since according to 14 CFR Part 77, not all obstacles may be considered hazards and would therefore not be in the D/DOF database. As previously stated for static data, vehicles operating on published flight paths may not be required to have on-board obstacle detection since the environment they operate in has built in obstacle protections.

Vehicle Situational Awareness – Airspace & Infrastructure Awareness

Static Data

Most airspace and infrastructure data does not change quickly and can thus be stored in static (pre-composed) databases. The FAA's Coded Instrument Flight Procedures (CIFP) codes in ARINC424-18 format airspace boundaries, airport, runway and facilities information. A complete listing of the encoded data can be found in the ARINC 424-18 standard.

Dynamic Data

Like obstacle data, NOTAMs are used to temporarily disseminate immediate changes to airspace and infrastructure components until they can be captured in the following data publication cycle.

Appendix B: DMS Mission Management Functions

The DMS mission functions constitute the top level of the DMS decision-making hierarchy:

1. Define mission objectives
    1.1. Destination
    1.2. E.g., firefighting
    1.3. E.g., surveying
2. Define mission constraints
    2.1. E.g., RTA
    2.2. E.g., RVSM requirements
3. Monitor conformance to mission constraints
    3.1. E.g., Determine if flight to the original destination is feasible
    3.2. E.g., Define action plans to recover delay
    3.3. E.g., Monitor destination field availability and capacity
    3.4. E.g., Monitor conformance to RTA constraints
    3.5. E.g., Monitor terminal weather for potential delays or diversion to alternate
    3.6. E.g., Define high, medium and low risk areas based on weather, terrain, obstacles, capability and trajectory
    3.7. E.g., Evaluate vehicle capability margins to accomplish mission objectives
    3.8. E.g., Evaluate pilot health status to accomplish mission objectives (e.g., requirement for immediate medical diversion)

Appendix C: Trajectory Management Functions

4. Manage conflicts
    - 4.1. Unpack conflict definitions from D-SA functions
    - 4.2. Analyze the capability margin for each conflict
    - 4.3. Analyze the compounded effects of conflicts on the capability margin along the trajectory
    - 4.4. Classify conflicts as hard (e.g., obstacle, terrain, traffic) or soft (e.g., icing, wind, traffic density)
    - 4.5. Prioritize conflicts for resolution
        - 4.5.1. Raise hard conflicts to the top of the priority list
        - 4.5.2. Prioritize hard conflicts (e.g., by time to encounter)
        - 4.5.3. Prioritize soft conflicts (e.g., based on capability margin)
    - 4.6. Resolve conflicts
        - 4.6.1. Adhere to statutory minimum terrain clearance requirements
        - 4.6.2. Avoid terrain
        - 4.6.3. Avoid obstacles
        - 4.6.4. Calculate optimal trajectory around conflict list
5. Manage Constraints
    - 5.1. Listen for constraint descriptions from D-SA functions
    - 5.2. Analyze the compounded effects of constraints on the capability margin along the trajectory
    - 5.3. Flag constraints that have the potential of negatively impacting future capability margins
    - 5.4. Monitor changes to known constraints (e.g., ATM constraints, TFR)
    - 5.5. Monitor actual and planned trajectory conformance to known constraints (e.g., geo-fencing, temporary flight restrictions, airspace boundaries)
    - 5.6. Monitor trajectory for new conflicts
6. Optimize Trajectory
    - 6.1. Prioritize optimization criteria: time, distance, energy, cost (e.g., user fees), other?
    - 6.2. Assess mission constraints
    - 6.3. Calculate optimized trajectory within constraints
    - 6.4. Calculate a conflict free optimized trajectory
    - 6.5. Relay optimized trajectory to trajectory manager

Appendix D: Digital Situational Awareness (D-SA) Functions

Terrain D-SA

7. Assess and disposition relevant terrain data
    - 7.1. Query Trajectory Management for known terrain trajectory constraint definition(s)
    - 7.2. Query the terrain support function for terrain data (e.g., mountain location & elevation, water bodies) relevant to the proposed trajectory
    - 7.3. Import processed terrain data from the terrain support function
    - 7.4. Update terrain constraint definition(s)
    - 7.5. Relay terrain constraint(s) data to Trajectory Management
    - 7.6. Determine if there is a terrain conflict (i.e., terrain on the proposed trajectory that exceeds the aircraft capability margin, e.g.: high terrain, landing field out of gliding range)
        - 7.6.1. Define terrain conflict(s)
        - 7.6.2. Prioritize terrain conflicts for resolution, if required
        - 7.6.3. Relay terrain conflicts to Trajectory Management

Obstacle D-SA

8. Assess and disposition relevant obstacle data
    - 8.1. Query Trajectory Management for known obstacle trajectory constraint definition(s)
    - 8.2. Query the obstacle support function for obstacle data (e.g., buildings, towers, cranes) relevant to the proposed trajectory
    - 8.3. Import processed obstacle data from the obstacle support function
    - 8.4. Update obstacle constraint definition(s)
    - 8.5. Relay obstacle constraint(s) data to Trajectory Management
    - 8.6. Determine if there is an obstacle conflict (e.g., tower and guy wires)
        - 8.6.1. Define obstacle conflict(s)
        - 8.6.2. Prioritize obstacle conflicts for resolution, if required
        - 8.6.3. Relay obstacle conflict(s) to Trajectory Management

Weather D-SA

9. Assess and disposition relevant weather data
    - 9.1. Query Trajectory Management for known weather trajectory constraint definition(s)

- 9.2. Query the weather support function for weather data (e.g., winds aloft, convective activity, icing, visibilities, etc.) relevant to the proposed trajectory
- 9.3. Import processed weather data from the weather support function
- 9.4. Update weather constraint definition(s) (e.g., wind profile)
- 9.5. Relay weather constraint(s) data to Trajectory Management
- 9.6. Determine if there is a weather conflict (i.e., weather on the proposed trajectory that exceeds the aircraft capability margin, e.g.: convective, ice, turbulence, volcanic ash cloud)
  - 9.6.1. Define weather conflict
  - 9.6.2. Determine if reconfiguring systems can resolve the conflict, and do so if it does
  - 9.6.3. Prioritize unresolved weather conflicts for resolution, if required
  - 9.6.4. Relay weather conflict(s) to Trajectory Management

Airspace & Infrastructure D-SA

10. Assess and disposition relevant airspace data
  - 10.1. Query Trajectory Management for known airspace and infrastructure trajectory constraint definition(s)
  - 10.2. Query the airspace support function for airspace data (e.g., Class B, Class C, prohibited, restricted, MOA) relevant to the proposed trajectory
  - 10.3. Import processed airspace data from the airspace support function
  - 10.4. Update airspace and infrastructure constraint definition(s)
  - 10.5. Relay airspace constraint(s) data to Trajectory Management
  - 10.6. Determine if there is an airspace conflict (e.g., active restricted airspace, active prohibited airspace, class B clearance required)
    - 10.6.1. If outside the airspace boundaries:
      - 10.6.1.1. Communicate request and/or intent to the controller
      - 10.6.1.2. If communication and/or intent is acknowledged:
        - 10.6.1.2.1. Relay trajectory instructions to DMS, if required
      - 10.6.1.3. If communication and/or intent is not acknowledged:
        - 10.6.1.3.1. Define airspace conflict(s)
        - 10.6.1.3.2. Prioritize airspace conflict, if required
        - 10.6.1.3.3. Relay airspace conflict(s) to Trajectory Management
        - 10.6.1.3.4. Broadcast intent on appropriate communication channels

    - 10.6.2. If inside the airspace:
        - 10.6.2.1. If airspace controller can be contacted:
            - 10.6.2.1.1. Advise of airspace penetration
            - 10.6.2.1.2. Relay airspace controller trajectory instructions to DMS, if required
        - 10.6.2.2. If airspace controller cannot be contacted
            - 10.6.2.2.1. Define airspace conflict(s)
            - 10.6.2.2.2. Prioritize airspace conflicts, if required
            - 10.6.2.2.3. Relay airspace conflict(s) to Trajectory Management
            - 10.6.2.2.4. Broadcast intent on appropriate communication channels

Traffic D-SA

11. Assess and disposition relevant traffic data
    - 11.1. Query Trajectory Management for known traffic trajectory constraint definition(s)
    - 11.2. Query the traffic support function for traffic data (e.g., number of aircraft in proximity, location of aircraft, trajectory vectors)
    - 11.3. Import processed traffic data from the traffic support functions
    - 11.4. Update traffic constraint definition(s)
    - 11.5. Relay traffic constraint(s) data to Trajectory Management
    - 11.6. Determine if there is a traffic conflict
        - 11.6.1. Analyze traffic trajectory vectors
        - 11.6.2. If traffic conflict resolution is required
            - 11.6.2.1. Prioritize traffic conflicts for resolution
            - 11.6.2.2. Determine if traffic is cooperative
                - 11.6.2.2.1. For cooperative traffic:
                    - 11.6.2.2.1.1. Handshake an avoidance maneuver based on mutually negotiated priority (e.g., capability margin, RTA, emergency status)
                    - 11.6.2.2.1.2. Relay conflict resolution trajectory change, if required, to DMS
                    - 11.6.2.2.1.3. Verify traffic complies with agreed upon maneuver
                    - 11.6.2.2.1.4. If not, treat as uncooperative traffic
                - 11.6.2.2.2. For uncooperative traffic:
                    - 11.6.2.2.2.1. Determine right-of-way (RoW) rules
                    - 11.6.2.2.2.2. Define traffic conflict

11.6.2.2.2.3. Relay traffic conflict, if required, to Trajectory Management

11.6.2.2.2.4. Verify traffic complies with RoW rules

11.6.2.2.2.5. If not, redefine traffic conflict

11.6.2.2.2.6. Relay traffic conflict to Trajectory Management

Appendix E: Digital Flight Visibility Functions

Terrain Visibility

12. Detect terrain (e.g., en-route, approach, landing surface)
    - 12.1. Receive Terrain D-SA function query
    - 12.2. Harvest relevant data
        - 12.2.1. Analyze terrain along active trajectory
        - 12.2.2. Collect procedural terrain data (e.g., published routings, MEA, MOCA), published instrument procedures, minimum sector altitudes, etc.
        - 12.2.3. Collect static terrain data (e.g., topographical maps)
        - 12.2.4. Collect active terrain data (e.g., sensors)
    - 12.3. Scrub the data
        - 12.3.1. Decode
        - 12.3.2. Generate an information quality factor (ICAO Annex 15 data attributes [4])
        - 12.3.3. Prioritize data according to quality factor
        - 12.3.4. Package the data
    - 12.4. Relay data package (e.g., latitude, longitude, elevation) to Terrain D-SA function

Obstacles Visibility

13. Detect obstacles (e.g., en-route, approach, landing surface)
    - 13.1. Receive Obstacles D-SA function query
    - 13.2. Harvest relevant data
        - 13.2.1. Analyze obstacles along active trajectory
        - 13.2.2. Collect static obstacle data (e.g., database)
        - 13.2.3. Collect active obstacle data (e.g., sensors)
    - 13.3. Scrub the data
        - 13.3.1. Decode
        - 13.3.2. Generate an information quality factor (ICAO Annex 15 data attributes [4])
        - 13.3.3. Prioritize data according to quality factor
        - 13.3.4. Package the data
    - 13.4. Relay data package (e.g., latitude, longitude, elevation) to Obstacles D-SA function

Weather Visibility

14. Detect weather (e.g., en-route, terminal)
    - 14.1. Receive Weather D-SA function query
    - 14.2. Harvest relevant data
        - 14.2.1. Analyze weather along active route
        - 14.2.2. Collect current and forecast weather data from external sources (e.g., ADS-B, FIS-B)
        - 14.2.3. Collect active weather data from sensors (e.g., RADAR)
    - 14.3. Scrub the data
        - 14.3.1. Decode
        - 14.3.2. Generate an information quality factor (ICAO Annex 15 data attributes [4])
        - 14.3.3. Prioritize data according to quality factor
        - 14.3.4. Package the data
    - 14.4. Relay data package to Weather D-SA function

Traffic Visibility

15. Detect traffic (e.g., close proximity, look ahead)
    - 15.1. Receive Traffic D-SA function query
    - 15.2. Harvest relevant data
        - 15.2.1. Collect traffic trajectory data from sensors (e.g., ADS-B, ADS-C, Mode-S)
            - 15.2.1.1. E.g., collect traffic aircraft type
            - 15.2.1.2. E.g., collect traffic distance to ownship
            - 15.2.1.3. E.g., collect traffic status
            - 15.2.1.4. E.g., collect traffic intent
            - 15.2.1.5. E.g., collect traffic flight plan
            - 15.2.1.6. E.g., collect traffic density
    - 15.3. Scrub the data
        - 15.3.1. Decode
        - 15.3.2. Generate an information quality factor (ICAO Annex 15 data attributes [4])
        - 15.3.3. Prioritize data according to quality factor
        - 15.3.4. Package the data
    - 15.4. Relay data package to Traffic D-SA function

Airspace & Infrastructure Visibility

16. Detect airspace and infrastructure (e.g., actual, look ahead)
    - 16.1. Receive Airspace & Infrastructure D-SA function query
    - 16.2. Harvest relevant data
        - 16.2.1. Collect data from external sources
        - 16.2.2. E.g., collect airspace and infrastructure availability and capacity (e.g., closure, charging availability, customs)
            - 16.2.2.1. E.g., collect NOTAMS
        - 16.2.3. Collect database data
            - 16.2.3.1. E.g., collect airspace requirements
            - 16.2.3.2. E.g., collect boundaries
            - 16.2.3.3. E.g., collect controlling agency information
            - 16.2.3.4. E.g., collect frequencies
    - 16.3. Scrub the data
        - 16.3.1. Decode
        - 16.3.2. Generate an information quality factor (ICAO Annex 15 data attributes [4])
        - 16.3.3. Prioritize data according to quality factor
        - 16.3.4. Package the data
    - 16.4. Relay data package to Airspace & Infrastructure D-SA function

Appendix F: DMS Support Functions

Communication (Vehicle-Vehicle or Vehicle-ATM)

17. Establish communications
    - 17.1. Determine which entities to communicate with
    - 17.2. Determine how to communicate with an entity (e.g., voice, data-link)
    - 17.3. Determine the target has received the message
    - 17.4. Monitor the continuity of the communication
    - 17.5. Determine the required level of response
    - 17.6. Adjust level of alertness based on actual level of response
    - 17.7. Prioritize multiple communications
    - 17.8. Accept or refuse a request to communicate
    - 17.9. Determine when an open link of communication should intentionally be interrupted
18. Communicate messages
    - 18.1. Communicate 4D Intent
    - 18.2. Request 4D Intent
    - 18.3. Communicate present state (e.g., location, velocity, etc.)
    - 18.4. Request present state (e.g., location, velocity, etc.)
    - 18.5. Communicate capability margins
    - 18.6. Request capability margins
    - 18.7. Communicate minimum safety volume
    - 18.8. Request minimum safety volume
    - 18.9. Request routing and data
    - 18.10. Share real-time weather, traffic, airspace data
    - 18.11. Negotiate traffic deconfliction strategy
    - 18.12. Negotiate arrival slot
    - 18.13. Declare emergency situation (Mayday)
    - 18.14. Declare urgent situation (Pan)
    - 18.15. Refuse an ATC instruction by communicating a reason, and/or an alternate instruction

Capability margin assessment

19. Locate energy intensive trajectory segments (e.g., hover, icing, night flight, etc.)
20. Locate regions along the trajectory where vehicle capabilities may be exceeded
21. Define areas of reduced number of alternate options
22. Determine available alternate landing areas
23. Define diversion plan trigger criteria
24. Generate diversion plans for regions of potential capability exceedances
25. Forecast capability margins along the entire trajectory
    - 25.1. Define much longer and farther can the systems operate for
    - 25.2. Define actual and forecast performance metrics
    - 25.3. Translate actual and forecast performance metrics into capabilities
    - 25.4. Compare the forecast and actual capability margins
    - 25.5. Compare the actual available power profile (APP) with the forecast
    - 25.6. Calculate minimum maneuvering safety volume

Establish Vehicle Awareness

Vehicle awareness functions provide the DMS with all relevant vehicle system health and capability data required to calculate, evaluate, and execute trajectories. In this decomposition, the pilot is considered as a non-deterministic vehicle system that, like other vehicle systems, affords the vehicle certain capabilities and must be managed.

Vehicle Health

26. Monitor systems health
    - 26.1. E.g., Monitor engine health
    - 26.2. E.g., Monitor Actual Navigation Performance (ANP)
    - 26.3. E.g., Monitor data health
    - 26.4. E.g., Monitor flight crew
        - 26.4.1. Evaluate physical health
        - 26.4.2. Measure engagement
        - 26.4.3. Determine compliance with DMS imperatives

Systems Management

27. Manage data
    - 27.1. Collect data

   27.2. Process data
   27.3. Distribute data
28. Manage powerplant
29. Manage electrical systems
30. Manage flight control systems
31. Manage hydraulic
32. Manage undercarriage
33. Manage braking system
34. Manage fuel system
35. Manage communication system
36. Manage pilot
   36.1. E.g., Provide relevant data in proper format for human DM
37. Etc...

Guidance & Control

38. Flight Control
   38.1. Actuate primary flight controls
   38.2. Actuate secondary flight controls
   38.3. Actuate trim controls
39. Ground Control
   39.1. Steer
      39.1.1. E.g., Actuate nosewheel steering
      39.1.2. E.g., Apply differential braking
      39.1.3. E.g., Apply differential power
   39.2. Decelerate
      39.2.1. Apply braking
      39.2.2. Apply reverse thrust
      39.2.3. Deploy drag devices
40. Automatic Flight Control
   40.1. Stabilize aircraft
   40.2. Manage aircraft energy (e.g., airspeed hold, vertical speed hold, Mach hold)
   40.3. Perform trajectory following

41. Engine Control
    41.1. Modulate engine power

Vehicle Capability Margin

42. Calculate Available Power Profile
    42.1. Define available time in hover, if applicable
    42.2. Define actual and forecast maximum power output
    42.3. Translate maximum power output into performance metrics
43. Define Icing capability
    43.1. Calculate available time in ice
44. Define Turbulence capability as a function of structural integrity, passenger comfort, cargo requirements
45. Define Landing surface capability as a function of undercarriage configuration
46. Define pilot capability as a function of engagement, data communicated, and health

Appendix G: KFMN – KGUP Flight

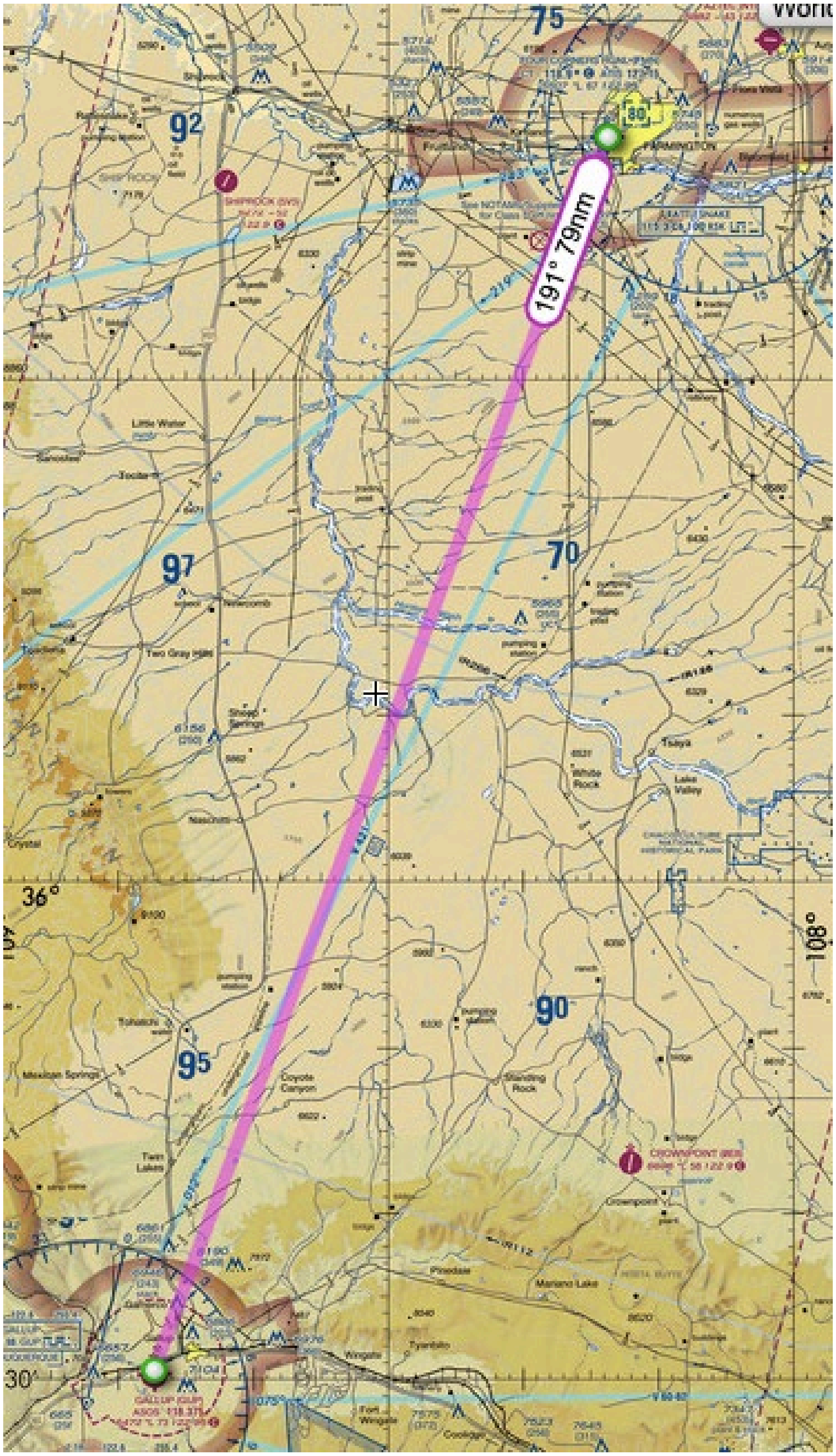

Figure 24: KFMN - KGUP direct flight plan (source: skyvector.com)

Appendix H: KFMN – KGUP typical flight (Empire Airlines)

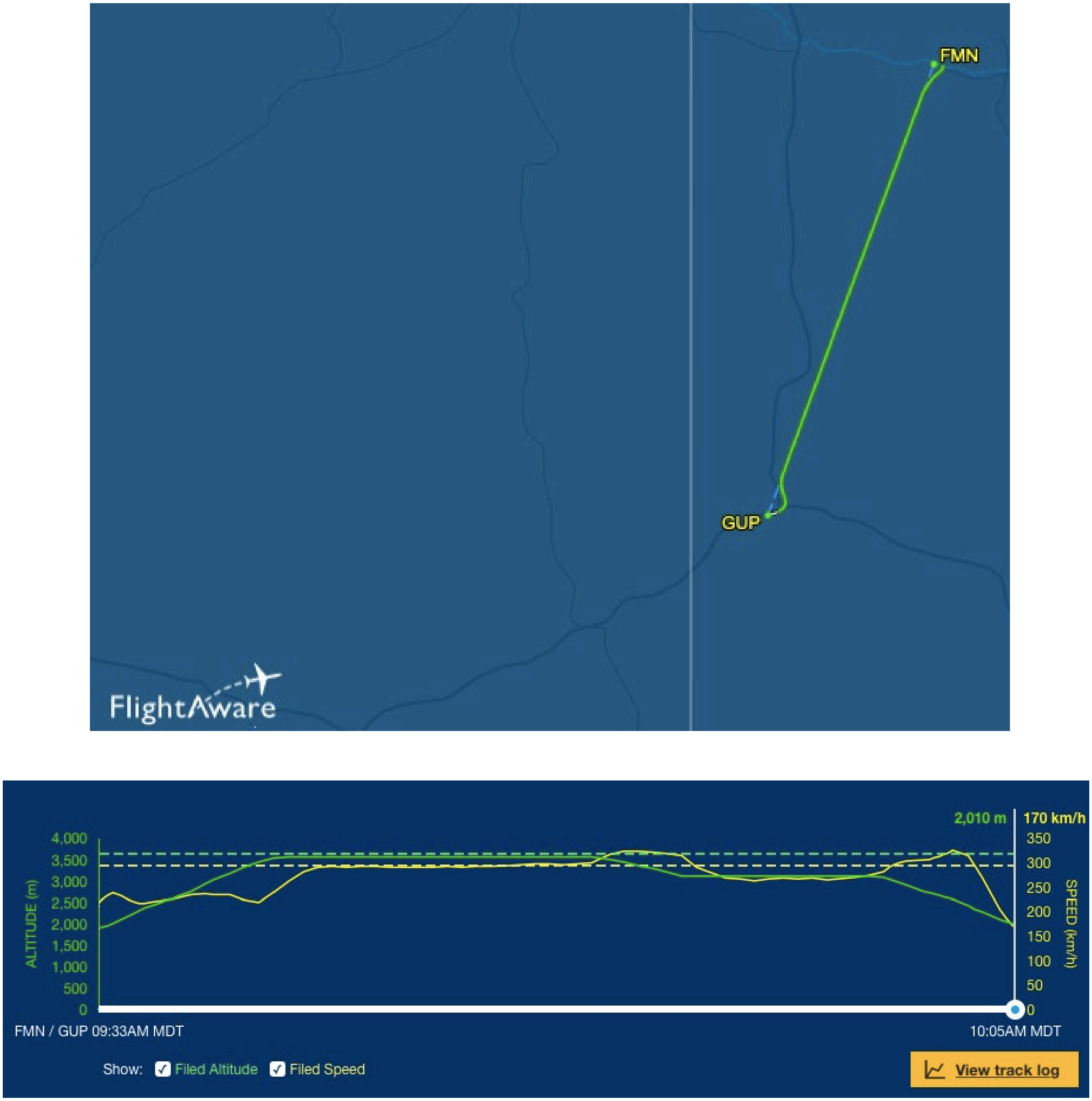

Figure 25: KFMN - KGUP typical flight profile with an initial climb to 12000 ft. The entire flight lasts approximately 35 minutes.

Appendix I: UAM Use Case Trajectory

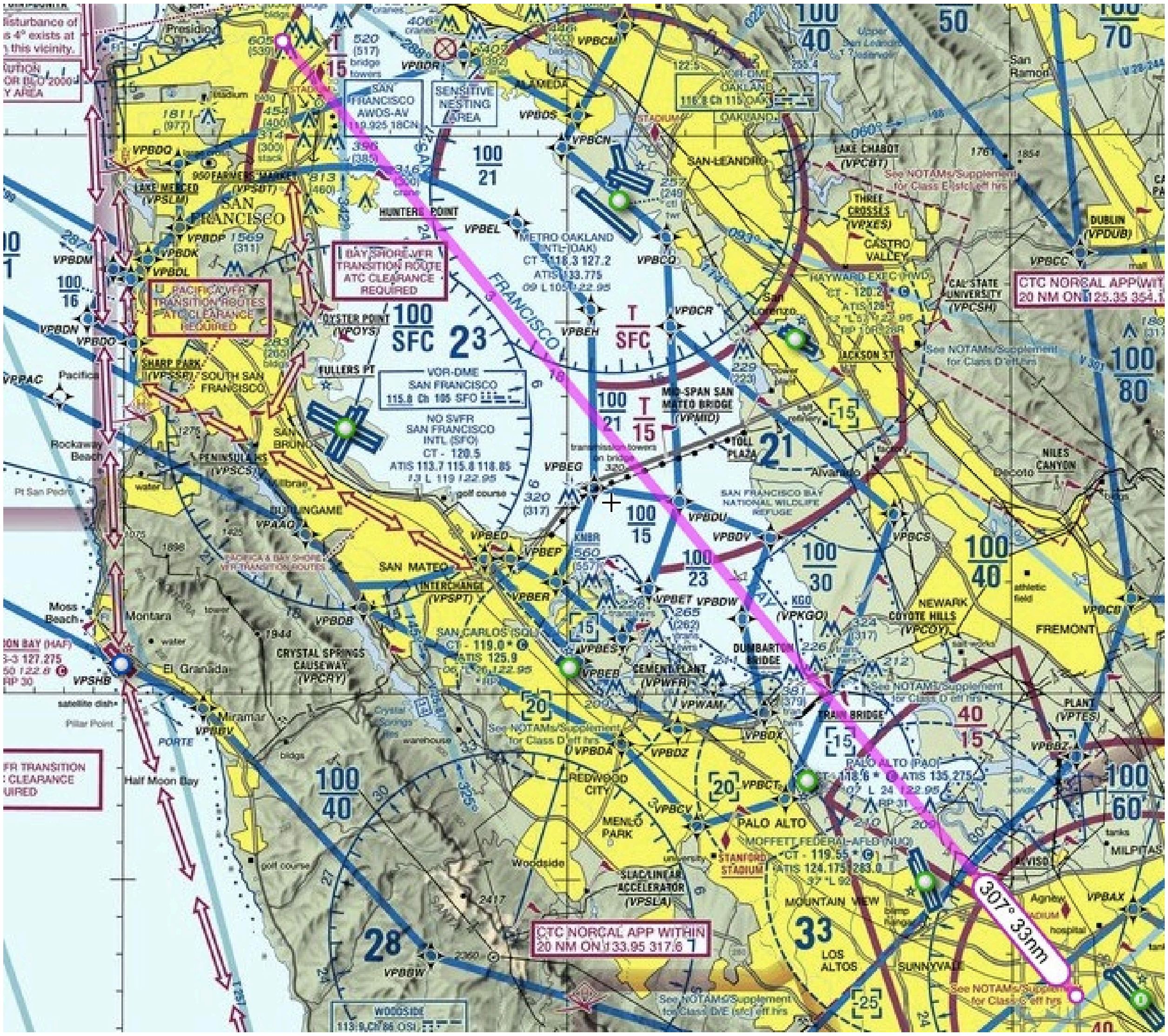

Figure 25: UAM use case trajectory departing San Jose, CA to San Francisco, CA.

Appendix J: Functions Ontology

The ontology is programmed in Web Ontology Language (OWL) in Stanford's Protégé software [37].

The ontology begins with a high-level categorization of concepts: Functions, Function Classifications, and Function Flows.

The Functions concept is further divided into:

1. Conflict & Constraint Analysis (CCA)
2. Capability Margins Assessment (CMA)
3. Communications (Comms)
4. Digital Situational Awareness (Digital_SA)
5. Decision Making System (DMS)
6. Miscellaneous
7. Trajectory Optimization (TO)
8. Vehicle Awareness (VA)
9. Digital Flight Visibility (Visibility)

The Function Classification concept is further divided into:

1. Active Function
2. Support Function

The Function Flow concept is further divided into:

1. Ordered Collection
2. Unordered Collection

Ordered Collections of functions are sequential arrangements of functions that must be executed in a specific order, and Unordered Collections are groups of functions that do not rely on ordered execution.

The ontology is also programmed with the following naming convention:

1. "FF_" denotes Function Flows
2. "F_" denotes Functions
3. "DFV_" denotes Digital Flight Visibility
4. "D-SA_" denotes Digital Situational Awareness
5. "CCA_" denotes Conflict & Constraint Analysis
6. "CMA_" denotes Capability Margin Assessment
7. "COM_" denotes Communications
8. "DMS_" denotes Decision Making System

Functions are then related through explicit properties. These properties enable the deduction of relationships between functions that are not made explicitly in the ontology, or that would otherwise be difficult to understand manually. The ontology enables these relationships to be made evident through user queries. As an example of how the ontology can be navigated, consider the functions shown in Figure 10, which contains the Terrain DFV function. In the ontology editor, "DFV_Terrain" can be queried, and the ontology returns 7 functions, as well as the parent concept, "Visibility." This tells the user that firstly, to have terrain DFV, 7 functions must be executed, and secondly that those functions are children of the "Visibility" concept. In the Protégé interface, the user can click on the returned functions, allowing them to navigate the functional flows, and further expose the functional relationships.

Continuing on the same example, querying "Digital_Flight_Visibility" returns 5 instances, including DFV_Terrain. For each query, protégé provides an explanation of the inference that led to the answer. In this case, two consecutive inferences are made to link DFV_Terrain to Digital_Flight_Visibility. The first of those two reveals that "DFV_Terrain hasVisibility FF_DFV_Terrain." This immediately tells the user that DFV_Terrain functions are organized in a Function Flow. Function flows have the following properties:

1. hasInitialFunction and hasLastFunction for ordered flows
2. hasFunction for unordered flows

Querying for "hasInitialFunction some Function" returns FF_DFV_Terrain, and the inference explanation provides the first function that must be executed to obtain terrain visibility.

Another method of revealing links is by utilizing Protégé's built in graphical mapping feature. The links that are discussed above are automatically graphed in block diagram form, as shown in Figure 10. The color-coded arrows display the relationships when they are hovered over with the cursor, and are not shown below. The "+" in the left-hand upper corner of certain boxes indicates that more relationships can be expanded, but have been collapsed for legibility.

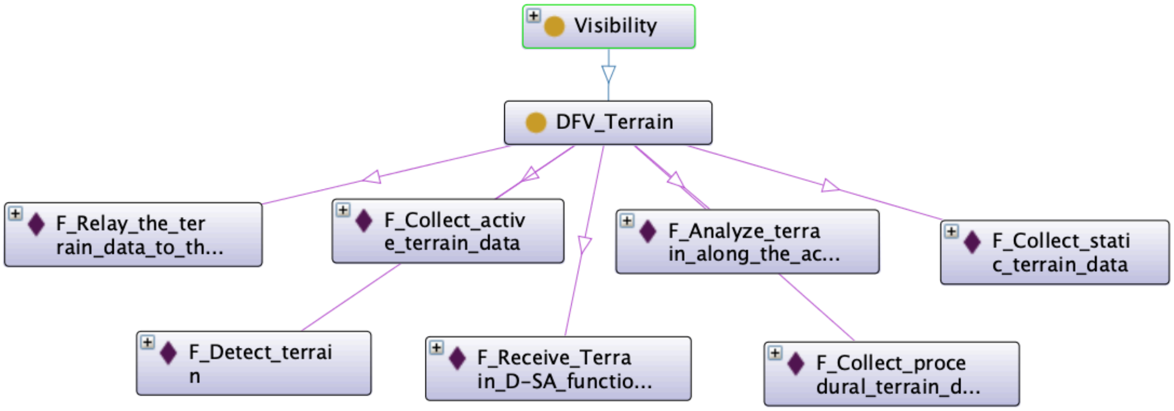

Figure 26: DFV_Terrain functions displayed graphically in the Function Ontology

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14. ABSTRACT

Advanced Air Mobility (AAM) demands greater levels of aircraft autonomy than are currently implemented today. To enable this requirement, novel aircraft functionalities and technologies as well as supporting airworthiness and operational regulations are required. A structured method to derive a comprehensive list of aircraft level decision-making functions is defined and applied. Paths to implementing the functions are generated by applying a structured four step method. Opportunities to implement novel technologies and functions are identified, and regulatory mechanisms supporting their implementation are underscored. The analysis demonstrates that aircraft autonomy is attainable in the medium-term.

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