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Applicability of Digital Flight to the Operations of Self-Piloted Unmanned Aircraft Systems in the National Airspace System

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Abstract

Unmanned Aircraft Systems (UAS) hold great promise for a new era of specialized missions, including personal air transportation, cargo flight operations, aerial surveys, inspections, firefighting and more. The anticipated market growth is significant. To unlock its scalability and incumbent benefits requires a human to oversee multiple flights simultaneously, focusing on multi-vehicle mission management and relinquishing to autonomous systems their active role in controlling the aircrafts' flight paths. Key to the realization of these scalability benefits is minimally-encumbered access to the National Airspace System (NAS), which poses some unique challenges for self-piloted UAS aircraft operations. These include the requirement for compatibility with existing airspace structures and operations including Visual Flight Rules (VFR) and Instrument Flight Rules (IFR), neither of which were developed to accommodate the unique needs and capabilities of UAS.

This paper explores the applicability of *Digital Flight* to the operations of self-piloted UAS. As proposed by NASA, Digital Flight is a flight operations capability, enabled by a set of cooperative procedures and digital technologies, in which flight operators ensure flight-path safety through automated separation and flight path management in lieu of visual procedures and Air Traffic Control separation services. Flights operating under potentially-forthcoming rules of Digital Flight employ advanced automation technologies, information sharing, connectivity to operational data, and cooperative behaviors through distributed decision-making to maintain safety and achieve mission objectives. Designed for integration with VFR and IFR operations in shared NAS airspace, potentially as a third set of flight rules, Digital Flight may provide the mechanism for UAS operators – and all aircraft operators – to scale and diversify their operations beyond what is achievable under current regulations.

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1. Introduction

Unmanned Aircraft Systems (UAS) hold great promise for a new era of specialized missions, including personal air transportation, cargo flight operations, aerial surveys, inspections, firefighting and more. The anticipated market growth is significant. In a 2018 report, the Aerospace Industries Association (AIA) estimated that, through 2036, larger UAS will drive nearly $150 billion in total spending and sustain up to 60,000 research and development (R&D), manufacturing, and service jobs [1]. The report also stated that while small UAS (sUAS) currently make up the lion's share of early adopters, *autonomous* larger UAS are poised to become more dominant due to their economic benefits, safety advantages, and consumer demand. In this context, *autonomy* is defined as the ability of an aircraft to operate independently, flying without a human directing the flight path or the aircraft executing only pre-programmed instructions. In fact, the unique feature of UAS is the absence of the onboard pilot, which not only makes these aircraft suitable for unique missions but also provides the opportunity for remote pilots to be responsible for more than one simultaneous flight (that is, increase the ratio of flight operations to human operators beyond 1:1). To unlock this aspect of scalability and its incumbent benefits requires a human to oversee multiple flights simultaneously, focusing on multi-vehicle mission management and relinquishing to autonomous systems their active role in managing the details of the aircraft's flight.

Key to the realization of these scalability benefits is minimally encumbered access to the National Airspace System (NAS), which poses some unique challenges for the navigation of self-piloted[1] UAS aircraft operations. In this context, UAS "navigation" is used in the broader context of *"Aviate, Navigate, and Communicate"* as used in RTCA DO-377 [2]. The term is applied to all functions that contribute to the definition and execution of the aircraft flight path, while also invoking additional Air Traffic Control (ATC) functions such as traffic separation. These functions include, but are not limited to, flight path optimization; terrain, obstacle, and weather avoidance; and traffic detection, deconfliction, and avoidance [3]. The supporting infrastructure, including the command and control link, is also a key element of UAS navigation.

The airspace access problem is analyzed below using the following framework:

- Implications of existing flight rules
- Unique UAS challenges
- Emerging concepts
- Long-term durability

[1] A self-piloted aircraft is an aircraft that does not require a human pilot to control the aircraft to maintain its flight path. Automation systems are responsible for all Aviate and Navigate tasks [4].

Several unifying themes are integral to the analysis. These include the requirement for compatibility with existing airspace structures and operations including Visual Flight Rule (VFR) and Instrument Flight Rule (IFR). Further, operational convergence is important to reduce divergent complexity; in other words, the intent is to avoid invoking an expanding number of tailor-made solutions for each emerging type of operation that may lead to segregated, single-use airspace. As Airbus notes, single-use airspace *"is more complex, less flexible, and restricts what is possible in the future"* [5].

This paper explores the applicability of *Digital Flight*, proposed in [6], to the operations of self-piloted UAS. **Digital Flight is a proposed flight operations capability, enabled by a set of cooperative procedures and digital technologies, in which flight operators ensure flight-path safety through automated separation and flight path management in lieu of visual procedures and ATC separation services.** Flights operating under the rules of Digital Flight employ advanced automation technologies, information sharing, connectivity to operational data, and cooperative behaviors through distributed decision-making to maintain safety and achieve mission objectives. Designed for integration with VFR and IFR operations in shared airspace, potentially as a third set of flight rules, Digital Flight may provide the mechanism for UAS operators – and all aircraft operators – to scale their operations beyond what is achievable under current regulations [6].

Implications of Existing Flight Rules

A specialized aerospace working group identified a key problem with the existing regulatory environment for UAS operations:

> *"Technology and regulatory gaps exist today…that are preventing citizens and the government from benefitting from the advantages of greater vehicle autonomy in the aerospace and transportation sectors. These gaps can only be closed through close, lock-step, collaboration… by industry and regulators"* [7] *.*

Nowhere are these problems more apparent than in the two fundamental types of flight operations in the NAS: VFR and IFR. The choice between VFR and IFR entails difficult tradeoffs and compromises between airspace accessibility and operational flexibility.

VFR operations are generally very flexible with decision-making distributed among individual pilots who have limited or no interaction with ATC (depending upon airspace class). The tradeoff is that a VFR flight is explicitly prohibited in some classes of airspace and is limited to Visual Meteorological Conditions (VMC). Moreover, by their nature, VFR operations are tactical operations with no required strategic planning component, which often results in uncertainty associated with the flight trajectory, duration, and time of arrival at a destination. For entities that are providing aerial mobility services to consumers, operational predictability will be important for their business operations.

Conversely, IFR flight can be conducted in most classes of airspace in both VMC and Instrument Meteorological Conditions (IMC). Operating IFR requires the sharing of operational intent (i.e., filing a flight plan), conforming to ATC system constructs and limitations, obtaining an ATC clearance, squawking an assigned transponder code, and following ATC instructions.

The physical separation requirements associated with IFR operations as well as controller workload constraints are limiting factors in the number of simultaneous operations that can occur in a geographic region. As an example, in most terminal areas there is a requirement for IFR flights to be separated by three nautical miles laterally and 1000 feet vertically. Traffic volumes in individual ATC sectors are typically limited to one to two dozen aircraft to prevent controller overload [8][9]. These factors would significantly limit the number of short-duration, UAS flight operations under IFR, especially in airspace with already dense traffic. In contrast, VFR flights must remain "well clear" of each other which implies a less restrictive physical distance. VFR is also characterized by decision-making distributed among aircraft which scales directly with the number of flights.

Airbus notes that today's VFR and IFR constrain UAS operations and preclude *"the introduction of new capabilities like automation in a safe and extensible way"* [5]. Specifically, current centralized Air Traffic Management (ATM) is already conceptually incapable of integrating at the envisioned operational tempo of Urban Air Mobility (UAM). Britain's Aerospace Technology Institute (ATI) anticipates a $210-360 B global market for the combined cargo UAS, UAM, and sub-regional markets [10] *subject to the successful deployment of these technologies*.

In summary, five primary motivations suggest that a third alternative to today's flight rules (VFR and IFR) may be needed to enable future Advanced Air Mobility (AAM) options to include UAM, UAS, and other increasingly automated flight operations:

1. **Operational Flexibility:** There is a desire for VFR-like flexibility to enable AAM operations at scale in all classes of airspace.
2. **Scalability:** Current ATC procedures associated with IFR operations are human-centric and require physical aircraft separations that significantly limit the number of operations in a geographic region. IFR operations are not likely to be able to scale to the anticipated operational tempo envisioned for AAM, whether it be electric vertical take-off and landing (eVTOL) aircraft conducting UAM operations or sUAS delivering parcels.
3. **Procedure Compatibility:** Self-piloted UAS aircraft cannot conform to current VFR and IFR requirements and procedures. There is no pilot to operate with visual reference to the ground, see-and-avoid obstacles and other aircraft, follow visual procedures, or communicate with and accept clearances from ATC.
4. **Operational Predictability:** Most electric powered aircraft will not have the option that fuel powered aircraft have of increasing their energy stores prior to take-off to account for operational uncertainties (e.g., vectoring, holding, speed controls or other delays enroute and at the destination) because they will often be operating close to their maximum range (accounting for required safety reserves). An unexpected delay may constitute a large percentage of the entire planned flight duration. Operational predictability provides that, when the flight departs, the operator can be reasonably certain that it will encounter minimal changes to its flight path and overall enroute time.

5. **Congestion Independence:** The growth of runway-independent operations and operations at non-towered regional and rural airports could be constrained by current ATC procedures. Operators departing non-towered airports under IMC into controlled airspace must request an ATC clearance, the receipt of which can be time-consuming due to one-in-one-out procedures. Also, congestion at major airports occasionally create airspace bottlenecks that impact operations that do not have the congested airport as a destination.

Unique UAS Challenges

RTCA lists a number of assumptions for UAS operations, including the following [11]:

- *UAS Operations will not degrade the current level of safety.*
- *Unmanned aircraft operations will not adversely affect the operational efficiency of other airspace users any more than the addition of an aircraft of the same type with a pilot on board.*
- *Routine UAS operations will not require the creation of new or modification of the existing special use airspace.*
- *UAS will comply with ATC instructions, clearances, and procedures when under ATC control.*

Achieving these goals poses several unique integration challenges. These include regulatory, operational, and technical hurdles, some of which are discussed below.

Regulatory Challenges

In their 2017 final report, the Drone Advisory Committee (DAC) stated:

> *"The existing set of IFR rules is most likely not well suited to handle dynamic operations of UAS conducting aerial work on a routine basis. In practice, we appreciate the need for regulations similar to those currently categorized under IFR, especially Communication, Navigation, and Surveillance (CNS) equipage and obstacle/terrain clearance. Recent work on operational environments and use cases conducted by MITRE and shared with the DACSC (Drone Advisory Committee Subcommittee) acknowledge this gap in the regulatory regime, which is exposed by UAS but may not (sic), eventually, be applicable to airspace users beyond UAS. It is widely recognized that the technology that would fully enable this operational goal for UAS has yet to be fully developed"* [12] .

Federal Aviation Regulations (FAR), 14 Code of Federal Regulations (CFR) § 107, addresses the operation of sUAS aircraft (less than 55 lbs). Key among these rules is 14 CFR § 107.31 *Visual line of sight operation* that requires "*the remote pilot in command, the visual observer (if one is used), and the person manipulating the flight control of the small unmanned aircraft system must be able to see the unmanned aircraft throughout the entire flight."* Among many important additional limitations, the regulations preclude:

- Operations in Class B, Class C, or Class D airspace or within the lateral boundaries of the surface area of Class E airspace designated for an airport without prior ATC authorization (§ 107.41);
- Operations above 400 ft above ground level (AGL) with some exceptions (§ 107.51);
- Operations over humans with aircraft that weigh more than 55 lbs (§ 107.110).

Operations of larger UAS aircraft, and operations Beyond Visual Line-of-Sight (BVLOS), have even greater restrictions. Essentially, each operation must be individually approved, which sometimes entails the creation of temporary flight restrictions (TFRs) reducing access to other operators (mainly eliminating VFR operations); the requirement for a chase aircraft; and/or a mechanism for detection and avoidance of other traffic (including both VFR and IFR). These restrictions are inconsistent with UAS operations at scale, particularly in high-density airspace which cannot be partitioned to support such specialized operations.

In addition to the difficulties imposed by the existing regulations, the *lack* of enabling regulations and technical standards is equally challenging due to the large number of potential stakeholders involved with any regulatory changes (e.g., emerging and legacy aircraft operators, manufacturers, regulators, and Air Navigation Service Providers). Still to be determined is which FAA organization will oversee the technical standards for operational integration of UAS and for the Associated Elements that are key to their safe operation [13].

Significantly, the DAC articulated the following goal: ***"a set of operational rules that provide the flexibility of operations under VFR but while flying by reference to displays and instruments without natural visual reference"*** [12]. This goal aligns precisely with the proposed capability of Digital Flight, described below.

Operational Challenges

NASA's *Pathfinding for Airspace with Autonomous Vehicles* (PAAV) project identified separation assurance and trajectory management as among the key technical barriers for the deployment of large inter-city cargo UAS [14]. In addition to traffic deconfliction and collision avoidance, such aircraft will have to work collaboratively with ATC-controlled terminal area traffic. This will entail predictable return-to-course behavior following flight path deviations for traffic, weather, or other factors.

The challenges faced during normal operations are exacerbated during contingency and emergency operations, such as lost link procedures in high density airspace. For example, a UAS should consider traffic density and population density in its execution of a lost link procedure. The decision to continue to destination or execute an immediate diversion to the nearest airport will depend upon the type of contingency and the specifics of the situation. Aircraft that could emulate human processes for "intelligent" flight-path decision-making and contingency planning would facilitate the broader integration of UAS operations in the NAS.

Technical Hurdles

There are many technical impediments to the widespread integration of larger UAS in the NAS that must be overcome. Two examples are a limited communications spectrum and communications latency. The problem is acute for safety-critical functions performed by the envisioned Providers of Services for Urban Air Mobility (PSU). Industry guidance is limited. RTCA DO-377 states: *"other than for the Communicate activity…no standards currently exist to support the direct assessment of the latency requirement for C2* [command and control] *link systems. However, latency must be considered…"* [2]. The same source limits latencies to approximately 150-200 milliseconds for UAS voice communication functions, but the operational aspects of maintaining such voice communications across numerous ATC sectors during routine BVLOS UAS operations are still undefined. Clearly, any on-board capability that mitigates the impacts of communication bandwidth and latency would be highly advantageous for integrating BVLOS UAS in the NAS in large numbers.

Another technical hurdle is the ability to "detect and avoid" (DAA) other aircraft, especially when those aircraft are operating under VFR without cooperative surveillance equipment. The guidance for non-cooperative sensor systems is, so far, limited to onboard radar systems and does not address electro-optical (EO)[2], LIDAR[3], or other technical solutions.

A further technical hurdle for UAS–NAS integration relates to traffic metering, such as terminal sequencing and arrival spacing. If UAS operations are to be seamlessly integrated with operations at major airports, they must have an autonomous ability to self-separate and to respond to the high-level spacing and sequencing requirements associated with busy terminal areas. This will require the implementation of cooperative or autonomous traffic management capabilities that are not currently embodied in aircraft having waypoint-driven navigation equipment.

The automation systems must be designed to manage the flight path at the "mission level" so that these aircraft behave in a manner that achieves separation goals and complies with performance-based CNS and behavioral standards. They must also continue to function and allow safe flight and landing under conditions of system degradation, failures, and unforeseen events in a manner similar to how a human pilot would be expected to act. This resilient autonomy design is a technical barrier that has not been satisfied by existing system design, architecture, and certification requirements.

Emerging Concepts

Three trends show particular promise for dramatically increasing UAS access to the NAS while maintaining the flexibility associated with VFR piloted operations. The first is the trend toward

[2] Electro-optical sensors use electromagnetic radiation detection and processing to produce an electronic signal.
[3] LIDAR is a commonly used term for light detection and ranging sensors that have evolved from applications that were associated primarily with determining distance to a point to sensors that can scan with multiple beams to form a three dimensional image.

performance-based regulation, which is supplanting specification-driven rulemaking. This is exemplified by Amendment 64 of 14 CFR Part 23 Airworthiness Standards: Normal Category Airplanes, that enables the use of consensus-based standards as a means of compliance, having a strong performance-based foundation. The second is the shift from specified equipment to *performance-based navigation* concepts, exemplified by Required Navigation Performance operations. The third is the subject of this paper, *Digital Flight*, which combines and expands these elements with information sharing and distributed, automated services for all operational safety functions, potentially supporting autonomous operations in all airspace categories and under all visibility conditions. The emerging concepts to enable BVLOS UAS operations rely upon sensors (e.g., radar, satellite navigation, Automatic Dependent Surveillance Broadcast or ADS-B, or other cooperative sensors) that are, for the most part, agnostic to flight visibility; thus the distinctions between VMC, Marginal VMC, and IMC have little practical impact on such operations. The one exception is EO-based sensing systems (i.e., cameras). There are several planned DAA system implementations that make heavy use of EO sensors either as a sole means of surveillance or in conjunction with other sensor modalities. There is some limited usage of LIDAR systems that also may be affected by atmospheric conditions. BVLOS operations will require a high degree of autonomous hazard detection and avoidance capability, regardless of the airspace class and flight visibility, and Digital Flight provides the context and technological backbone for allowing such operations.

Long-term Durability

Several key considerations will affect the long-term durability, effectiveness, and growth potential of large-scale UAS operations in the NAS. The DAC-recommended *"tiered approach to access based on risk, industry need, and ease of implementation"* [12] is a good starting point, as it combines the essential business elements with the safety imperative. Without satisfying both of these elements, there is no possibility for such an initiative to succeed.

A second consideration is that UAS operations in the NAS must be compatible with all current VFR and IFR operations in all classes of airspace and in all environmental conditions (i.e., VMC and IMC). The most effective solution would seamlessly support all these environments and regimes, while maximizing the utility of the aircraft. This would likely entail a new set of flight rules and associated technologies tailored for autonomous operations (piloted or unpiloted) that leverage existing aspects of both VFR and IFR.

2. Digital Flight

Digital Flight (DF) is a proposed flight operations capability, enabled by a set of cooperative procedures and digital technologies, in which flight operators ensure flight-path safety through automated separation and flight path management in lieu of visual procedures and ATC separation services. DF is envisioned as a generalized new operating mode applicable to potentially all aircraft types and operations in all classes of airspace. Like VFR and IFR, DF would be established as a formal regulatory basis to routinely conduct flight operations under a prescribed set of operating rules designed to ensure safety of flight in a populated airspace. A 2020 NASA publication proposed that DF be formalized as an optional *third set of flight rules* alongside VFR and IFR, i.e., Digital Flight Rules (DFR) [6]. The intent of DF is to enable legacy and emergent operations alike to leverage the advanced technological capabilities and benefits of DF in the achievement of their diverse and expanding operational goals. Just as IFR and VFR operations can coexist in the same airspace today, it is expected that DF operations will – by design – be able to coexist with both IFR and VFR operations in the same airspace.

Two foundational principles of DF are *ensuring safety at scale* and *empowering operator flexibility* in the airspace. Taken together, these principles establish the bedrock declarations that the DF operator (1) **is directly responsible for the safety of flight through cooperative conflict management even in high-traffic environments**, and (2) **has broad airspace access and significant operational flexibility in the airspace.** Under DF, ensuring safety while exercising these freedoms is realized by the DF operator conducting real-time, self-directed, flight-path decision-making for each flight, enabled through reliance on at least *four critical elements* (each described in more detail in the upcoming section "Critical Elements"): sharing of operational telemetry/intent, connectivity to operational data, cooperative operating practices, and flight path management automation. These dependencies distinguish DF from operations conducted under VFR and IFR. Under VFR, the pilot relies on visual perception, situation awareness gained from monitoring voice frequencies, and established procedures (e.g., traffic patterns, memorized right-of-way rules) to remain well clear. Under IFR, the pilot relies on communications with ATC, separation services, and clearances to manage conflicts.

In DF, the operator does not rely on visual perception or other direct observations for situation awareness but on information received from sensor technology, connectivity, and other critical elements to create the necessary situation awareness to manage conflicts and their overall operations. This enables airspace access in both VMC and IMC, and it enables the flexibility that comes from self-management of their operations. Given that the information received is not limited by visual line of sight, operators will have information that will enable them to increase their planning horizon beyond the visual horizon and act strategically in the management of potential conflicts.

Operator Benefits

For the DF operator, the potential benefits of DF are significant. *Access to the airspace* stands to be dramatically improved. Unless operating at congested airports, IMC will not significantly impede access nor require the operator to choose between waiting for an IFR clearance and waiting for visibility to improve before taking off under VFR. Surface operations and airborne hazards on departure would be the primary limiting factors to airspace access for DF operators. Once airborne, the DF aircraft's flight path may proceed through almost any part of the airspace, not restricted to ATC-assigned routes or altitudes, or limited by class of airspace, provided cooperative operating practices are followed to avoid disruption. Mixed operations (i.e., sharing the airspace with VFR and IFR operators) are designed into DF from the outset, with non-interference being a priority. The result is routine airspace access for DF operators, regardless of the type of operation or type of aircraft, a critical factor in enabling the business models of commercial operators.

Also significant are the DF benefits of *operational flexibility* in the airspace. Operational flexibility essentially equates to an operator's authority, while airborne, to replan the flight path as often as desired, to any extent (small or large), without delay, and without needing external approval. VFR flights generally have this type of flexibility in Class E and G airspace, provided the intended flight path change is consistent with VFR requirements such as flight visibility, clearance from clouds, and appropriate altitudes. However, even VFR operational flexibility is limited by the visibility requirement and the challenges of effective longer-range replanning. For DF operators, their connectivity to over-the-horizon operational data means that the visibility imposes no such limitation on operational flexibility (though it may still be required for aircraft control, depending on equipage and pilot rating). Under IFR, operational flexibility is restricted by a number of factors, including the need to request and receive approval of route changes from ATC, the impracticality of making frequent requests, the limits on route changes ATC will approve, and the delay sometimes incurred in receiving approval. Operational flexibility under DF is not impacted by these factors. DF operators' determination of desired flight paths is, for the most part, only limited by their responsibility to cooperatively manage conflicts, remain consistent with distributed rules of behavior, and to ensure the safety of flight. As demand for scarce capacity resources occurs (e.g., Final Approach and Take Off area (FATO) landing slots), DF operations may have some additional constraints. While this would temporarily restrict certain maneuvers in proximity to traffic and other hazards, in general it provides for a great deal of agility and spontaneity in flight operations.

Together, better airspace access and greater operational flexibility create a broad opportunity for more efficient operations, innovative applications, and the emergence of new markets. Small UAS operations at low altitudes are just beginning to explore the possibilities of market generation, leveraging newfound access to little-used airspace under 400 feet and within visual line-of-sight. With DF, these barriers could conceivably be eliminated. Proposed UAM concepts [15][16] aim to take this opportunity even further with constructs and procedures that rely not on government ATC services but on operator capabilities and a network of regulated commercial service providers. Some proposed early constructs involve containment inside traffic corridors, with self-managed procedures inside. With full DF operations, this segregation can be overcome, allowing operators to better integrate with legacy traffic which will help meet the growing and geographically diversifying demand. In Upper Class E airspace, where ATC services are necessarily limited, DF would serve the increasing variety of operations, especially those that depend on real-time flexibility. Generally, DF would benefit any operation that depends on or benefits from on-demand airspace access and flexible or frequent replanning, whether due to the nature of their mission or to the dynamic unpredictability of the stochastic airspace operating environment. These are just some examples of the opportunities that DF may unlock. Fig. 1 illustrates the benefits of DF relative to VFR and IFR.

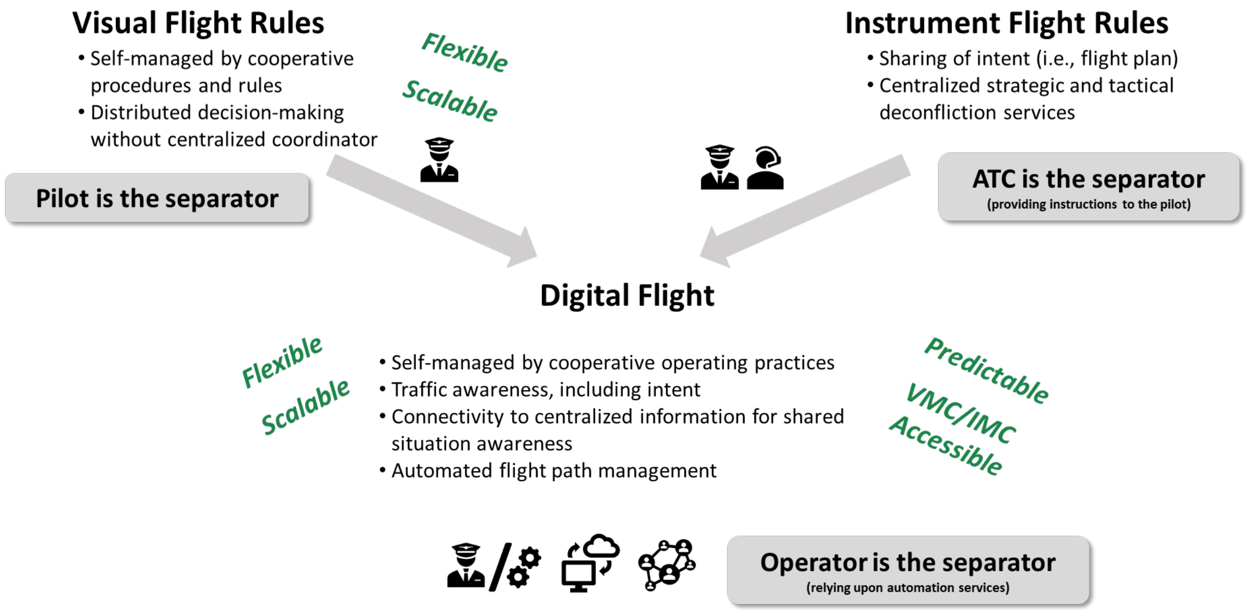

Fig. 1. Digital Flight combines beneficial attributes of VFR and IFR.

Essential Features

To be authorized to participate in DF operations, the DF operator must shoulder the responsibility of ensuring the safety of the aircraft's flight path with reliance on the DF critical elements described below. Two essential features enable DF adaptability to the differing needs of various types of operations. The first is regulator-authorized *"collaborative and responsible automation"* employed by DF operators in meeting their flight-path safety responsibilities. Goodrich and Theodore [17] define this term in the context of UAM to indicate "*automation which is assured to perform specified functions such that human monitoring and mitigation of potential failures of those functions is no longer necessary.*" In other words, a DF hazards analysis would not include an assumed reliance on the pilot or an air traffic controller to ensure the safety of the aircraft's flight path in the event of automation failure to perform this function (therefore setting a high bar for automation reliability or the inclusion of automated reversionary modes).

The second essential feature is architectural flexibility. DF operators may self-provide the needed functions via airborne and/or ground-based implementation, or they may employ FAA-regulated private entities to provide services to the DF operators to meet their responsibilities. An example of self-provisioning with airborne implementation is the concept of airborne self-separation relying upon sensors and information feeds for a digital model of the traffic environment, which has been the subject of R&D internationally for several decades. Recently, the model of third-party service provision, as the basis for both strategic and tactical conflict management, is being explored in the United States and internationally as part of the emergent concepts, technical standards, and initial deployments associated with UAS Traffic Management (UTM) and UAM [15][18].

By embracing either construct or a combination of self-provision and third-party services, DF is flexible and adaptable to various implementations and architectures. Remaining as an essential requirement, however, is the DF operator having the ultimate responsibility for flight safety including traffic separation.

Critical Elements

At least four critical elements enable DF. They are: *sharing of operational telemetry and intent*, *connectivity to shared operational data* (creating a common operating picture), *cooperative operating practices, and flight path management (FPM) automation*. Each are described below.

First, as part of the cooperative process of conflict management, DF operators must share their operational telemetry and, to the extent appropriate to their mode of flight and at the appropriate time, share their intent with other operators and update the intent in flight.[4] While this promotes predictable behavior, it does not imply that the operator is locked into the shared intent, but rather that changes in intent be declared in a timely fashion. DF operators must also continuously share telemetry of their current flight status to include at least their current position, altitude, heading, speed, and vertical velocity (similar to ADS-B messaging). Depending upon the cooperative operating practices defined for DF, additional flight status messaging may include current energy/fuel state, purpose of the flight (some flights such as public safety or medical emergencies may have priority over other flights), and specific performance limitations.

The second key element is connectivity to operational data. Two aspects are important here: the connectivity and the operational data. Connectivity is growing rapidly in aircraft operations through broadband data links creating an increasing interconnectedness of systems onboard with ground systems [19]. With the advent of the *connected aircraft*, the "big picture" is no longer the sole purview of ground systems. This real-time data access (which may require recertification for safety-critical connectivity) enables the DF operator to build and maintain an up-to-date model of the operating environment, like a "digital twin" of the local airspace tailored to their operational needs. The operational data feeding this model can conceivably be as diverse as the operational environment itself, though particular data elements are key. For DF, the most important elements are wind field predictive model data and measurements (for accurate trajectory predictions), traffic state data (via ADS-B or a similar system certified for higher criticality), traffic intent data (to the extent available), weather hazard data, terrain and obstruction data, data on any other dynamic hazards such as special activity airspace, and landing facility (e.g., runway, FATO) status. Depending on the nature of the DF operation, the level of integrity and content to ensure safety may vary, and other data categories may be required.

The third critical element for DF is the automated application of cooperative operating practices. Cooperation here is founded upon the common goal of ensuring safety at scale so that all

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[4] Allowances would be made for some aircraft operations that require tactical maneuvering with limited or no intent, such as when navigating around weather or when conducting spontaneous searches and survey missions.

operators may enjoy the maximum use of airspace with minimal restrictions. Generally, cooperation under DF would be exemplified in several ways: sharing information, following rules and procedures, behaving predictably, distributing burdens equitably, coordinating maneuvers when necessary, and not knowingly creating conflicts for others to solve. These cooperative operating practices will enable operators to manage conflicts in a distributed fashion which will allow operations to scale as demand grows and operations diversity. When conflicts emerge naturally (a virtual certainty, given the dynamic uncertainties in the operating environment), cooperative behavior dictates that the burden of conflict resolution be equitably shared through established right-of-way rules. Given the expanding diversity of operations, such right-of-way rules under DF would necessarily be algorithmically implemented and automatically applied to account for the much broader set of factors that must be considered beyond conflict geometry. Such factors may include the flight rules status of the involved aircraft, performance capability margins, the degree of intent sharing, imposed constraints (e.g., time of arrival), and emergency status. When time is short requiring both aircraft to maneuver, right-of-way rules would be supplanted by intentional maneuver coordination to ensure the maneuvers are complementary.

As the fourth and final element described here, FPM automation plays a central role in creating, monitoring, evaluating, and revising the DF vehicle's flight path throughout the flight to ensure it is protected from hazards while achieving mission objectives and adhering to the cooperative operating practices which have been established. Under VFR, the pilot is the flight path manager, and under IFR, FPM functions are shared between at least two entities, the pilot and the air traffic controller. Under DF, operator-distributed automation performs these FPM functions in support of the pilot (or for self-piloted UAS as a fully automated system). In surpassing the limitations of humans and centralization, FPM automation promotes safety at scale while empowering the operator with unprecedented decision-making and flexibility. Initial design guidelines for FPM automation based on lessons learned through prototype R&D by NASA are presented in [20]. The paper describes five principal objectives of FPM automation, namely, to establish and maintain a flight path that is *feasible* regarding aircraft performance and airspace constraints, *deconflicted* from proximate traffic and other known hazards, *coordinated* with other aircraft and service providers, *flexible* to enable future replanning if needed, and *optimal* from the operator's business perspective and/or the airspace system. Together, these characteristics contribute to the safety of DF and the benefits to the DF operator, other nearby operators, and the overall airspace system. They also establish the basis for DF to be defined as a performance-based operation.

Fig. 2 illustrates the FPM automation's central role in processing data in at least four categories: (1) Operational Environment, (2) Navigation, (3) Traffic, and (4) Command, Control and Coordination. The FPM automation is the integrator, and as such, it ingests, analyzes, and processes the incoming data. It outputs key data elements for dissemination to external agents such as the operational intent, vehicle-to-vehicle (V2V) coordination data, and aircraft capability margins.

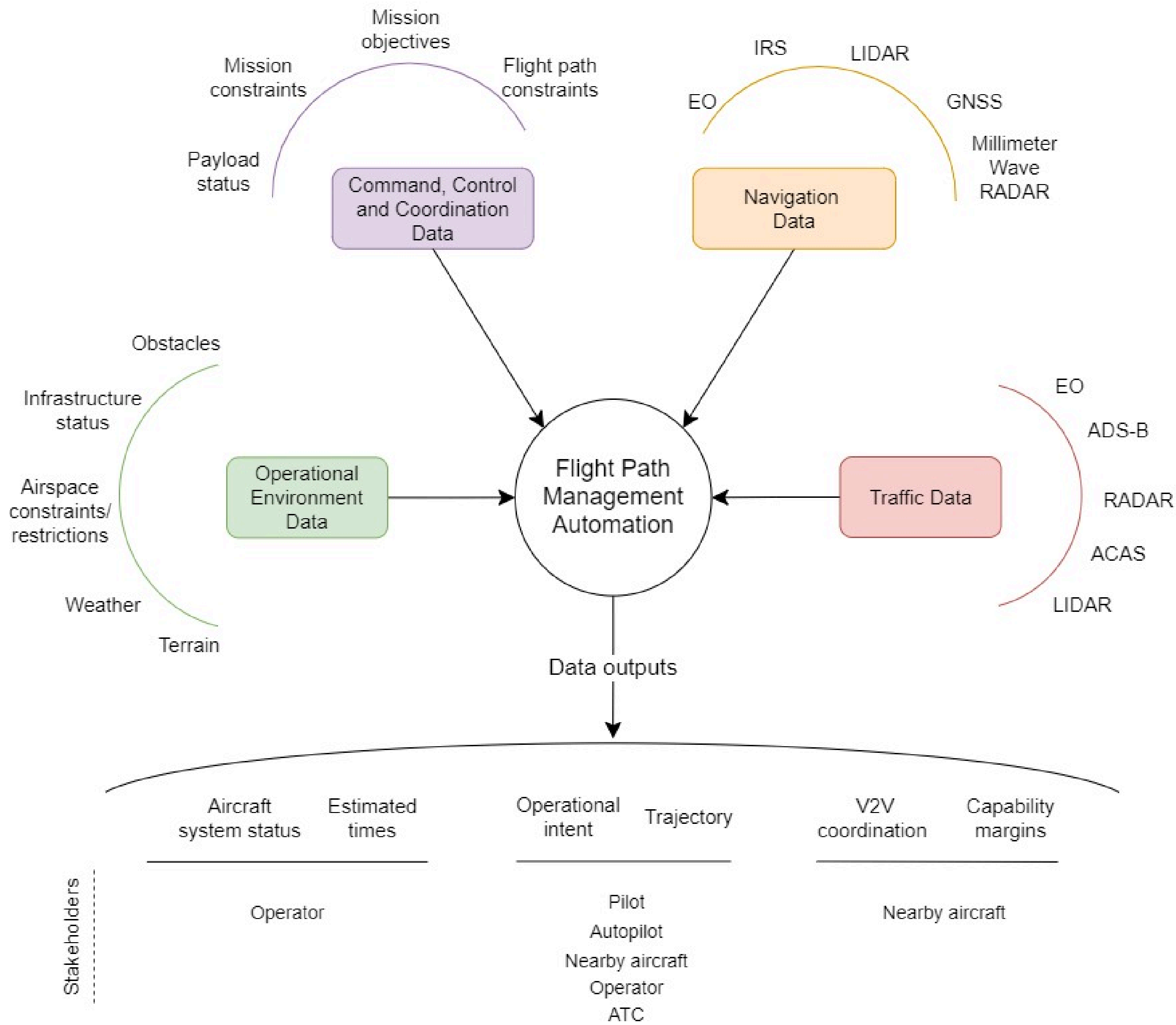

Fig. 2. Digital Flight employs a variety of data exchanges with systems onboard and external to the aircraft to provide safety-critical functionality and coordinated operations in the airspace.

Widespread Applicability

DF is presented here as an *operational capability* rather than a unique concept of operation to emphasize its flexible applicability to the many existing and emerging concepts of operation. Just as VFR and IFR are ubiquitously available (provided the rules' requirements are met), DF should be available *to all operators and types of operations* (not just UAS), with few if any exceptions. The nature of the specific operation may dictate specific DF performance requirements. For instance, a DF aircraft interacting with VFR or IFR aircraft may need to resolve conflicts with those aircraft at greater time horizons and with larger separation values than if interacting exclusively with other DF aircraft. Aircraft maneuver agility may similarly drive DF performance requirements. Slow-to-react aircraft or those with limited maneuvering degrees of freedom may need to act sooner than more nimble aircraft. Research will be needed to sort these issues out.

The key point is that DF should be viewed as a new operational capability applicable to potentially all aircraft types and operations as long as they can satisfy defined performance requirements in all classes of airspace.

DF is not a replacement, nor a displacement, of existing flight modes. Rather it complements VFR and IFR capabilities as a third alternative with unique attributes. It will not penalize or impact VFR and IFR operators or burden air traffic controllers, but rather will share the airspace equitably and cooperatively. As mentioned, it is not a competitor to emerging concepts like UAM, but rather an enabler to be integrated with those concepts. It is also not a complete system design. Rather, it is one element – a key element – working in concert with other critical services and infrastructure, like those that support VFR, IFR, and ATC, but founded on emerging digital technologies and infrastructure. DF is supported by an ecosystem of connectivity, data sources, automation technologies, and operational rules, and the combined capability of this ecosystem is the foundation for the new operating authority. DF is not a limited delegation procedure but is the operator's choice at flight time. From an operational perspective, DF is envisioned as a sustained authorization, persistent from take-off to landing, unless the operator chooses purposefully to switch to either VFR or IFR. DF is also not a free-for-all. It carries responsibilities for cooperative behavior, information sharing, and safety assurance. Its collaborative capabilities may also assist in traffic complexity management and traffic flow management. Lastly, DF is not expected to be a static capability. In line with the latest methods of certification and approval, it is envisioned to be performance-based, which allows for incorporation of continuing technology advances. As such, DF is a foundation for long-term innovation.

Regulatory Implementation

Because DF is an emerging vision, there are different possible regulatory paths that could be considered for its implementation.

- **Formal Set of Flight Rules:** DF could be implemented as a third complementary set of formal flight rules, alongside VFR and IFR with modifications to 14 CFR Part 91 and perhaps some portion of 14 CFR Part 135 and Part 121 as well. This allows it to be designed precisely to meet the need, while minimizing changes to the rules for VFR and IFR. However, it also means it must be generalized to support all types of operations, potentially defined with variations in performance requirements for each operational type that would use it.

- **Operation-Specific Flight Rules:** DF could be implemented as a suite of operation-specific operational rules, similar to 14 CFR Part 107, that contains operational rules and procedures for sUAS flight under 400 feet, or 14 CFR Part 93, that contains Special Air Traffic Rules for specific geographic areas. Each type of operation would have its own unique version of DF appropriate for that operation, and these versions may not be interoperable. This would create a complex patchwork of rules with possibly strict segregation and potentially hazardous interplay at the boundaries.

- **Augmented VFR:** VFR regulations and procedures could be modified to include digital situation awareness and decision-making as an optional augmentation to visual capabilities. Traditional VFR must be preserved while accommodating the significant differences of DF, which could be a challenge in rulemaking.
- **Enduring Delegation Under IFR:** Another option is to embed DF as an enduring delegated operation within the IFR clearance, issued pre-flight and lasting the whole flight. This would essentially accommodate DF as an IFR operation, but it also may complicate or confuse the roles and responsibilities of pilots and controllers with safety-critical implications.

All of these will require some degree of rulemaking informed by community engagement and R&D, as well as test, evaluation, and demonstration activities.

3. UAS Operational Examples

To illustrate the potential application of DF to the operations of UAS, two hypothetical operational examples are given. The first example applies to sUAS and describes an emergency response scenario in which the sUAS operator deploys an aircraft in a first responder role, employing the capabilities of DF to quickly access the site and operate flexibly to meet mission needs. In the second example, a larger, intercity UAS cargo aircraft conducts time-critical product delivery in IMC.

Small UAS

A local sheriff's department receives a call from a railroad dispatcher that there has been a derailment of a freight train that includes several cars carrying anhydrous ammonia and some cars carrying chlorine gas. The site of the derailment is in grazing ranchland, several miles from any road, and so emergency road vehicles are unable to quickly access the scene. There is concern about poisonous gas drifting toward a farming community three miles from the derailment. As shown in Fig. 3, the site is also in proximity to the approach path to a regional airport.

The sheriff's office contacts a local UAS operator to request on-scene surveillance to determine the extent of damage to the rail cars carrying hazardous cargo and to check the direction and distance any leakage might be spreading. The weather in the area contains widespread fog and low ceilings, necessitating flight in IMC.

Under these circumstances, the weather precludes VFR. Conventional procedures necessitate flight under IFR with its attendant compromises, namely a restricted flight path, compliance with ATC instructions, and large traffic separation standards with other aircraft. To safely manage the influx of aircraft and its sudden increase in workload, ATC re-routes traffic arriving at the regional airport to a different runway to keep them well clear of the site of derailment. Departing traffic must adjust their flight plans to take into account the runway change, which may have cascading effects on the rest of their flight plan.

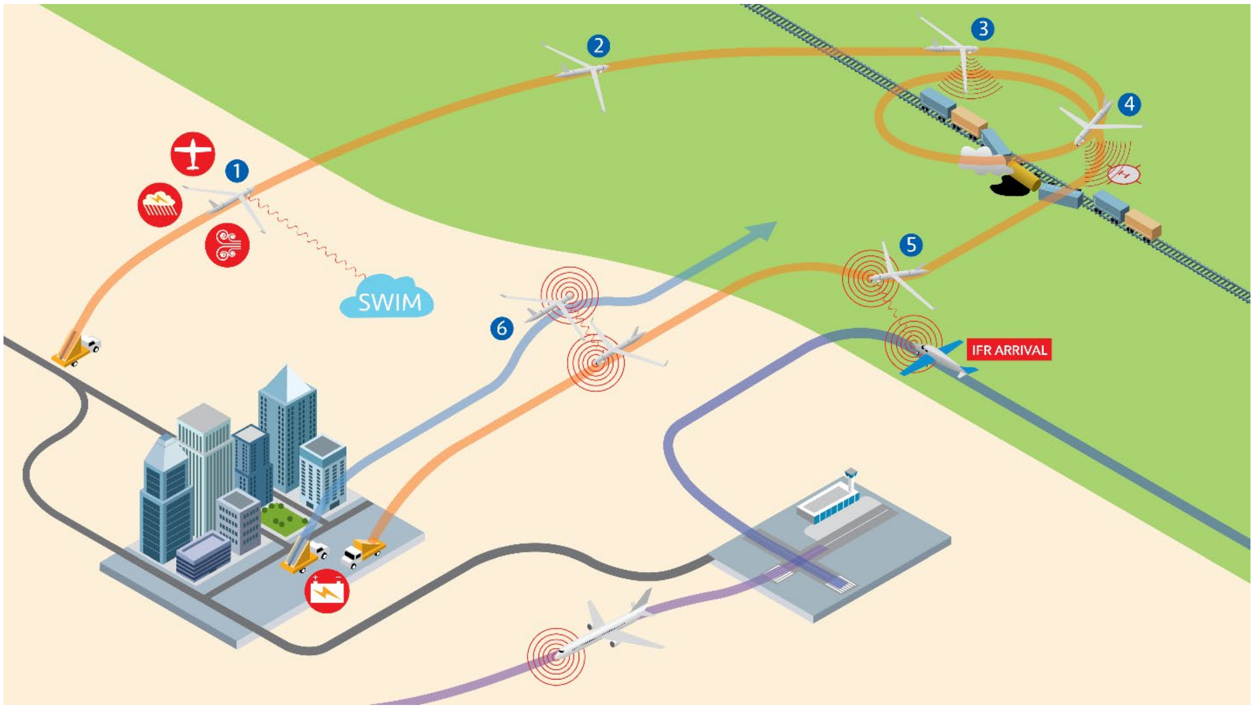

Fig. 3. A small UAS mission employs Digital Flight to respond to a train derailment. Graphic by R. Neale.

To avoid IFR limitations and to avoid disruption to concurrent operations at the airport, the operator opts to conduct the flight under DF rules (Fig. 3, sequence ① through ⑥). Strong tailwinds at 2000 feet AGL will provide the fastest access to the accident site, and the flight will traverse Class G and E airspace. A simplified flight plan containing the origin, destination coordinates, and remote identification is automatically sent to the ATC computer prior to liftoff. Both the standard ADS-B system and the "ADS-B like" system used by sUAS below 400 feet AGL will be operated throughout the flight, providing position, altitude, and state data to the air traffic system and any nearby aircraft. Operating under DF rules, the drone must maintain the required ATC separation distance from IFR aircraft approaching and departing the nearby regional airport. There are no VFR flights in the area, because of the weather.

The UAS aircraft powers up its C2 data communications and initializes its onboard FPM automation system (capable of managing the entire flight, should the C2 link be lost). Prior to departure, the FPM automation was updated with the latest operating picture (winds, weather, airspace restrictions), local traffic intent information, and mission parameters. As the flight lifts off, this information is updated and will continue to be updated during flight using the digital connectivity infrastructure (①). Traffic state information will be received directly from aircraft broadcasts.

Approaching the train wreck, the drone descends (②) using its terrain database and camera systems (once below the cloud layer) until reaching the destination coordinates. The remote ground control station operator now takes over visually through a video data feed to scout the train for signs of dangerous chemical leakage (③). The operator quickly finds a car that has rolled over into another derailed car, making a gash in the tank from which massive clouds of thick white smoke are spewing. The exact coordinates of the spot are marked, and the direction of the local wind is determined from the drone heading. Regardless of the locally low visibility, the onboard FPM system maintains digital situation awareness through a steady stream of updates to its digital model of the dynamic operating environment, received through ground links, airborne broadcasts, and onboard sensors. The damage to the car, locations of train crew members, and location and direction of the chemical spill are relayed to the sheriff, who has now activated a county disaster office to coordinate the response.

The drone locates the best spot for a helicopter landing zone for emergency personnel upwind from the spill and relays its coordinates and a photo of the spot (④). Low on battery energy, the drone is re-directed to a charging station in a nearby town. At the same time, a relief drone is sent from the same location to take over surveillance. Enroute to the charging station, the drone's FPM automation detects a conflict with a descending General Aviation (GA) aircraft (⑤), as well as with the approaching relief drone (⑥). Right-of-way rules encoded in the algorithms of the FPM automation confirm that the UAS aircraft must yield to the GA aircraft, while V2V communication with the relief drone assures cooperative deconfliction. Applying the appropriate separation standard for the two aircraft pairings, the FPM automation computes a route change to achieve the required separation. The system has been preconfigured by the UAS operator to automatically execute it. Under DF rules, the operator is authorized to rely on automation to be responsible in such contingency situations.

As the ceiling lifts later in the day, helicopter operations with emergency personnel supplement the drone flights that continue to supply needed equipment and surveillance for the planning office. When the weather becomes VMC in the Class E and G airspace, EO detection of non-cooperative VFR aircraft supplements the ADS-B surveillance to maintain safe separation. The departure and final approach areas of conventional airports, when in use by conventional piloted aircraft, are avoided by dynamic geofencing. Each time the UAS aircraft approaches its destination, the FPM automation updates its arrival path based on sensed winds and local obstructions and traffic, while using onboard sensors to ensure a clear landing spot.

Intercity UAS

A fixed-wing, single-engine utility aircraft is part of a large cargo fleet regularly transporting high value and perishable goods from distribution centers located on or near major airports in the city to local and private airports throughout the region. The flight conditions today are IMC, and the aircraft is carrying Yttrium-90 isotopes used to treat cancer. Because the isotopes have a short half-life (~70 hours), it is imperative that the time sensitive cargo be delivered as quickly as possible. To meet this requirement, the operator opts to conduct the flight under DF rules. The aircraft's DF capability is enabled by V2V data link for surveillance; air-ground connectivity for monitoring, control, and in-flight access to operational airspace and weather data; and onboard FPM automation.

As depicted in Fig. 4 (sequence ① through ⑥), the departure takes place from a non-towered airport, and prior to lining up on the runway, the onboard FPM automation updates its operating environment model and appropriately sequences its departure in the active traffic pattern. An

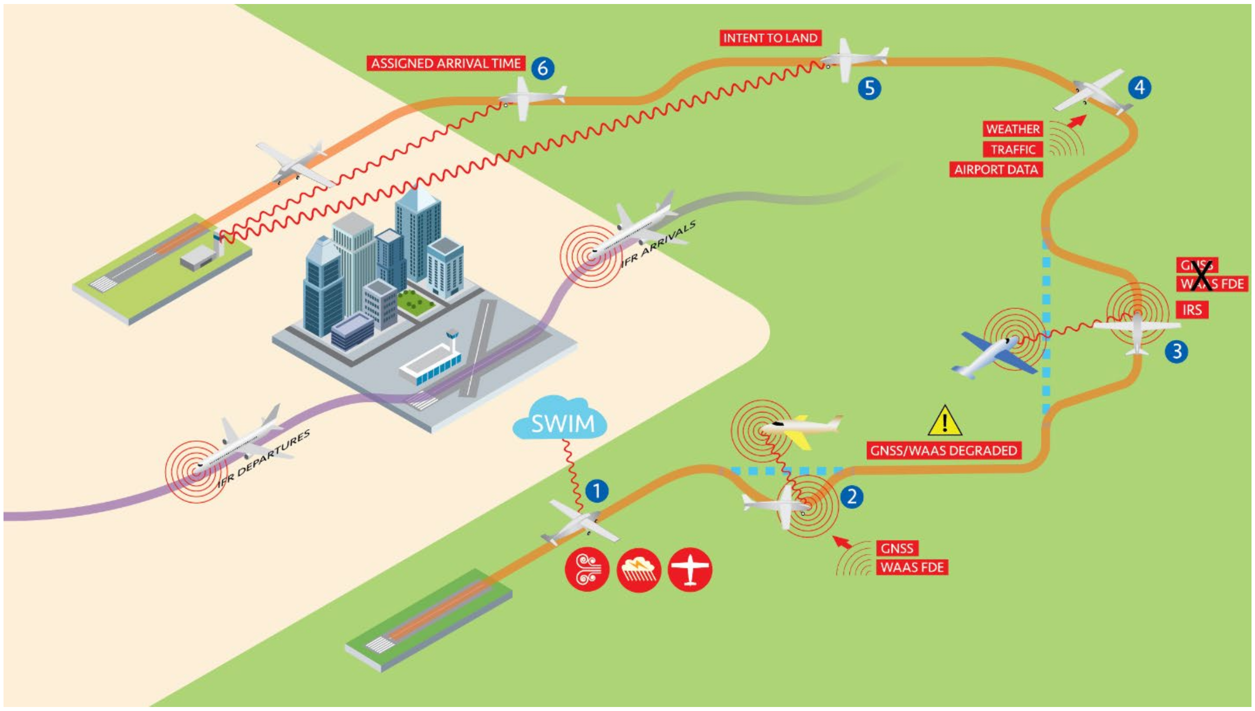

Fig. 4. A UAS aircraft employs Digital Flight in an inter-city cargo delivery mission. Graphic by R. Neale.

automated voice message announces the departure on the local radio frequency. As the autonomous aircraft lifts off, the actual departure time and intended flight path are transmitted to the System Wide Information Management (SWIM) service provider for use by other operators (①). Cooperative behavior is rewarded under DF; transmitting four-dimensional intent will earn this aircraft elevated right-of-way privileges should it encounter other DF aircraft transmitting less detailed intent data. Regardless, flights operating under DF rules yield right-of-way to IFR and VFR traffic.

Once airborne, the onboard FPM automation system ingests V2V surveillance data and, leveraging air-ground connectivity, continually updates its model of the operating environment. FPM automation system functions are activated to continuously monitor, evaluate, and revise the flight path when needed for safety or to improve flight efficiency. Coordinated flight path changes are also designed to preserve flexibility for future revisions while balancing optimization objectives. These FPM functions act together to ensure that, given available aircraft performance, the selected flight path is operationally feasible relative to airspace restrictions, traffic, obstacles, terrain, and weather.

Using adaptive separation criteria unique to DF, the FPM automation system applies custom criteria specific to each traffic aircraft it encounters. The criteria may depend on a variety of factors, including flight rules in use, intent data shared, encounter geometry, navigational precision, aircraft maneuvering capability, and energy stores. Currently enroute, the aircraft is registering full Global Navigation Satellite System (GNSS) signal strength and nominal Wide Area Augmentation System (WAAS) Fault Detection and Exclusion (FDE) status, allowing the smallest separation criteria to be applied. An upcoming encounter with another DF aircraft proves the point (②). The minimum separation criteria applied to this encounter enables the two flights to pass in close proximity, well below IFR separation minima, with at most a minor change in course required. Under IFR, both aircraft would have needed to adjust their course to pass at least five miles from each other.

Shortly after the traffic encounter, a navigation system monitor detects an unexpected degradation in GNSS service, resulting in a less accurate measurement of position for all aircraft. As the aircraft automatically switches to an Inertial Reference System (IRS) for primary navigation, the FPM automation responds accordingly by increasing its trajectory prediction uncertainty bounding. Correspondingly, traffic separation criteria are increased to compensate for the added uncertainty of the inertial system (③). Other than this automatic adjustment to require greater separation from traffic based on the less-precise navigation performance achieved by the IRS navigation system, all DF functions and procedures remain unaffected, and the flight continues. As long as the prediction errors can be conservatively bounded, no other contingency procedures need to be invoked.

The aircraft operator is aware that the arrival airport is proximate to a major hub conducting a significant volume of IFR operations. As the FPM configures for arrival, it searches its on-board databases and loads the approach and departure paths of the hub into its operational model (④). It then ensures that any flight path changes it makes remain well clear of them. This way, the DF aircraft effectively yields right-of-way to the IFR traffic.

Given the volume of arrivals of various cargo aircraft to the destination regional airport, a metering service is in effect, assigning arrival sequence based on first-come, first-served criteria and issuing nominal touchdown times to maximize throughput. The FPM relays its intent to land and its arrival time estimate to the metering service (⑤), and it listens for an assigned arrival time through a data link service (⑥). Upon receipt, the FPM assigns the required time of arrival (RTA) as a constraint on flight path generation. All subsequent noise-abatement and conflict-resolution flight path adjustments will maintain conformance to the RTA constraint to the extent consistent with safety. Nearing final approach, the flight establishes the appropriate interval behind the traffic ahead in sequence to maximize runway throughput.

However, as the aircraft begins its final approach, its on-board FPM automation system detects a conflicting VFR aircraft, forcing a missed approach (not shown in Fig. 4). As a result, conformance to the original RTA is no longer possible, and the FPM system requests a new time from the metering service. The aircraft calculates a new return flight path that meets the constraint and executes it, landing safely. A courier meets the flight on the ramp and rushes the medicine to the adjacent hospital for use.

As a result of the arrival performance contribution from this and other DF aircraft, traffic flow into the regional airport is maximized. Meanwhile, ATC is not burdened by this traffic and maintains focus on the IFR arrivals and departures at the hub airport.

4. Conclusion

Evidence is accumulating that the current airspace structure and its associated VFR and IFR flight procedures are constraining the evolution of the air transportation system. Among the operational visions impacted are UAM operations in and around Class B, C, and D airspace; the integration of BVLOS UAS into the NAS; and highly scalable operations available to all operators through deployment of advanced automation and procedures.

Existing VFR and IFR constructs entail a difficult compromise between operational flexibility and all-weather airspace access. Operational flexibility requires visual conditions, whereas access regularity requires an ATC clearance that limits the operator’s flexibility. This compromise will impede the emergence of increasingly diverse airspace utilization concepts that seek to leverage modern technological advancements, especially as VFR/IFR operations are rooted in 50-100 year-old legacy concepts such as “flight visibility” and “see and avoid,” which have little meaning in the digital age, particularly for autonomous aircraft.

Digital Flight is proposed as a new operational mode for maintaining the flexibility inherent in VFR while retaining the all-weather access of IFR. DF takes full advantage of emerging technologies such as traffic-compatible flight path optimization (exemplified in NASA’s “Traffic Aware Strategic Aircrew Requests” project, [21]), advanced sensors and data links, and advanced aircraft automation for flight path management. DF will explicitly remain compatible with IFR/VFR operations in the shared airspace but will yield significant operational advantages for the DF operator. These include: “VFR-like” operational flexibility to intelligently replan the flight under dynamic airspace and weather conditions; reduced separation standards between DF-equipped aircraft allowing higher-density operations; traffic deconfliction that accounts for aircraft performance margins and maneuvering capabilities; increased predictability and throughput using collaborative time-of-arrival capabilities, and automated traffic-compatible flight path optimization. In addition, the aircraft operational autonomy that is at the heart of DF should reduce voice and data frequency congestion for manned and unmanned aircraft operations, thereby addressing a key challenge to increased all-weather airspace access.

Performance-based DF operations can be implemented in an incremental fashion, starting today, by taking advantage of existing airspace structures and procedures, along with available technologies such as ADS-B and Traffic Alert and Collision Avoidance System (TCAS). The full implementation of DF requires cyber-secure data connectivity, cooperative operating practices, and onboard FPM automation. Connectivity is already emerging rapidly [18]; FPM research has produced initial design guidelines to industry [20] and already has yielded early applications such as TASAR [21]; and air-to-air cooperation already has a precedent in the use of TCAS for coordinated collision avoidance. The scope of DF-like operations will undoubtedly further increase with the maturation and safety-critical certification of each of these elements, but much could be accomplished in the very near future on the path toward full DF regulatory implementation.

Two examples were used to illustrate the potential near-term advantages of DF compared to VFR and IFR. In the sUAS emergency response scenario, DF enabled a safety-critical operation that would have been impossible using VFR and IFR alone. The use of DF gave unprecedented "VFR like" access to the accident site that would not have been possible under VFR or Part 107 in the prevailing weather. In parallel, the DF automation ensured that the aircraft did not impinge on the IFR operations at the nearby airfield, without the need for ATC intervention or an IFR clearance. The intercity cargo-carrying UAS example illustrated how traffic capacity could be maximized at a hub airport without increasing ATC workload, due to the autonomous capabilities of the DF aircraft, the lower communications workload, and the reduced separation that could be instituted between pairs of aircraft operating under DF. It also illustrated a contingency scenario requiring a dynamic replan of the arrival, managed in coordination with ATC.

In closing, DF addresses several clearly-identified limitations within the existing airspace and procedural environments that will hamper the introduction of new airspace entrants, such as UAM in Class B-C-D airspace and self-piloted UAS aircraft conducting highly scalable operations. DF provides a tangible and achievable path for accommodating these sweeping changes to the air transportation system, while increasing all-weather airspace access and operational flexibility for *all* DF users (not just UAS). Existing VFR and IFR regulations as they exist today will be insufficient to address the needs associated with these new operations.

5. References

[1] Aerospace Industries Association, "Think Bigger: Large Unmanned Systems and the Next Major Shift in Aviation," https://www.aia-aerospace.org/uasreport2018/, accessed 11/2/2021, 2018.

[2] RTCA Inc., "Minimum Aviation System Performance Standards for C2 Link Systems Supporting Operations of Unmanned Aircraft Systems in U.S. Airspace," DO-377, Washington, DC, 2019.

[3] Vajda, Paul and Maris, John, "A Systematic Approach to Developing Paths Towards Airborne Vehicle Autonomy," NASA/CR–20210019878, NASA Langley Research Center, Hampton, Virginia, August 2021.

[4] ASTM, "Autonomy Design and Operations in Aviation Terminology and Requirements Framework," Technical Report-1 (TR-1 EB), ASTM International, West Conshohocken, PA, 2019.

[5] Airbus, "Blueprint for the Sky – A Roadmap for the Safe Integration of Autonomous Aircraft," https://www.airbus.com/newsroom/stories/premiering-a-future-blueprint-for-our-sky.html, accessed 11/2/2021, 2018.

[6] Wing, David J. and Levitt, Ian M., "New Flight Rules to Enable the Era of Aerial Mobility in the National Airspace System," NASA/TM-20205008308, Hampton, Virginia, November 2020.

[7] Aerospace Industries Association of Canada (AIAC), "Report on Recommendations of AIAC TICA Autonomous Sub-Committee," Sep. 22, 2020.

[8] Federal Aviation Administration, "Monitor Alert Parameter," Order JO 7210.3W, https://tfmlearning.faa.gov/publications/atpubs/fac/1708.html, accessed 11/2/2021, 2010.

[9] Song, Lixia, Wanke, Craig, and Greenbaum, Daniel P., "Predicting Sector Capacity for TFM Decision Support," AIAA-2006-7827, 6th AIAA Aviation Technology, Integration and Operations Conference, 2006.

[10] Aerospace Technology Institute, "Accelerating Ambition," Technology Strategy document, https://www.ati.org.uk/wp-content/uploads/2021/08/ati-technology-strategy.pdf, accessed 11/2/2021, 2019.

[11] RTCA Inc., "Guidance Material and Considerations for Unmanned Aircraft Systems," DO-304a, Washington, DC, 2021.

[12] RTCA Inc, "Drone Access to Airspace, Report of the Drone Advisory Committee, Final Report," https://www.rtca.org/wp-content/uploads/2020/08/dac_tg2_final_reccomendations_11-17_update.pdf, Washington, DC, 2017,accessed 11/2/2021.

[13] Federal Aviation Administration, "FAA Approval of Unmanned Aircraft Systems (UAS) Special Class UA Projects and their Associated Elements," Memo AIR600-21-AIR-600-PM01, Washington, DC, 2021.

[14] Informal discussion J. Maris (Advanced Aerospace Solutions) – K. Swieringa (NASA Langley Research Center) re *Pathfinding for Airspace with Autonomous Vehicles* (PAAV) project, October 2021.

[15] Federal Aviation Administration, "Urban Air Mobility (UAM) Concept of Operations v1.0," Washington D.C., 2020.

[16] Deloitte Consulting LLP, "UAM Vision Concept of Operations (ConOps) UAM Maturity Level (UML) 4," https://ntrs.nasa.gov/citations/20205011091, accessed 11/2/2021, 2020.

[17] Goodrich, Kenneth H. and Theodore, Colin R., "Description of the NASA Urban Air Mobility Maturity Level (UML) Scale," 2021 AIAA SciTech Forum, NASA Technical Report Server, Document ID 20205010189, January 2021.

[18] Federal Aviation Administration, "Unmanned Aircraft System (UAS) Traffic Management (UTM) Concept of Operations v2.0," Washington D.C., 2020.

[19] Gogo, LLC, "From the Ground Up: How the Internet of Things will Give Rise to Connected Aviation," Gogo, LLC, Chicago, IL, 2016.

[20] Karr, D. A., Wing, D. J., Barney, T. L., Sharma, V., Etherington, T. J., and Sturdy, J. L., "Initial Design Guidelines for Onboard Automation of Flight Path Management," 2021 AIAA AVIATION Forum, NASA Technical Report Server, Document ID 20210017484, June 2021.

[21] Wing, David J., "The TASAR Project: Launching Aviation on an Optimized Route Toward Aircraft Autonomy," NASA/TP-2019-220432, NASA Langley Research Center, Hampton, Virginia, 2019.

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14. ABSTRACT
This paper explores the applicability of Digital Flight to the operations of self-piloted UAS. As proposed by NASA, Digital Flight is a flight operations capability, enabled by a set of cooperative procedures and digital technologies, in which flight operators ensure flight-path safety through automated separation and flight path management in lieu of visual procedures and Air Traffic Control separation services. Designed for integration with VFR and IFR operations in shared NAS airspace, potentially as a third set of flight rules, Digital Flight may provide the mechanism for UAS operators – and all aircraft operators – to scale and diversify their operations beyond what is achievable under current regulations.

15. SUBJECT TERMS
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