PAAV Concept Document

Version 1.1

Submitted by Arwa Aweiss (PAAV Subproject Manager)
on behalf of the ATM-X PAAV Subproject.

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1.1	10/7/2022	Aweiss, Arwa (ARC-AFT) Hayashi, Miwa (ARC-AFH)	• The cover page was adjusted for the ATM-X PAAV subproject milestone deliverable submission purpose. • This version is approved for external release (NF-1676 process has been completed). • Acknowledgements section was added.	No change

Executive Summary

The Pathfinding for Airspace with Autonomous Vehicles (PAAV) Concept Document, version 1.0, lays out the key challenges and potential solutions for the use of uncrewed aircraft (UA) technology for future regional air cargo operations. The challenges and solutions described in this document were informed by communications with the UA industry community (e.g., RTCA, the Federal Aviation Administration, and regional air cargo business operators), as well as the PAAV team's research activities during the last two years including four tabletop exercises, a human-in-the-loop simulation study, a numerical simulation study, a functional allocation study, and flight data analysis (Appendix A).

This document first describes the expected operational context of PAAV (Section 2), such as the flight mission, baseline UAS components, nominal operations, m:N operations (i.e., "m" remote pilots per "N" aircraft), and off-nominal operations. This context sets the scope for the PAAV concept development work. PAAV concept development assumes that UA operations will be increasingly autonomous. Thus, near- and far-term assumptions are defined (Section 3).

PAAV identified seven key challenges for UA operations (Section 4):

- Flight route planning
- Separation and flow management
- Traffic pattern integration
- Contingency management
- Taxi, takeoff, and landing
- m:N operations
- Communications operations

The following 13 potential solutions to these challenges are then described (Section 5):

- Scalable communications architecture
- Data link
- Designated UAS corridors
- Crew planning for m:N operations
- Flight route optimization
- Traffic load-level control
- Trajectory solutions with data link
- Automated hazard avoidance for m:N operations
- Traffic pattern integration (TPI) tool
- Standard lost command and control (C2) link (LC2L) procedures
- Automated hazard avoidance under LC2L
- Auto-taxi, auto-takeoff, and auto-land
- Ground control station (GCS) user interface for m:N operations

The document attempts to link each of these solutions to one or more of the challenge areas. The following are some highlights:

- First a scalable architecture is needed to provide robust and reliable C2 and communication capabilities for the UA. This architecture will feature Voice Over Internet Protocol (VoIP) to provide direct voice communication between the pilot and the air traffic controller (ATC) rather than using the vehicle as a relay. In the far-term the architecture will support data communication which is critical to enable m:N operations. The architecture includes link management services which ensure availability of reliable C2, where needed along a flight, leveraging a network of satellite, radio, and cellular technologies, among others, that become available in the far-term.

- Second, the UA flight plan and route is constantly optimized for UA needs such as the availability of reliable C2 link, LC2L mitigation plans, and multiple remote pilots along the flight, among others. Such planning combines with crew management methods to provide adequate remote pilot resources during m:N operations.
- To reduce the amount of interaction between the UA and other traffic and with ATC, procedural and strategic methods may be employed. Examples of such methods include limiting the UA to airspace corridors within which airspace services are provided by third-party agents, and flow control methods that limit the number of UA in an airspace region to a level that keeps the interaction with other traffic minimal and acceptable. These measures may be particularly useful in the near-term as technologies (such as data communication and UA automation) and regulation (such as digital flight rules) evolve to support more seamless integration with other traffic and ATC.
- High levels of automation are needed for the UA and remote pilot to enable m:N operations. Such automation draws on digital, closed, trajectory-based solutions that generate complete trajectories for UA, accounting for conflicts with other visual flight rules (VFR) and instrument flight rules (IFR) traffic with any additional buffers, UA concerns such as C2 reliability and LC2L mitigation availability, and any airspace and flow constraints. These trajectories are uplinked automatically to the UA, reducing the remote pilot workload. In the far-term, these solutions can minimize the interaction with ATC by potentially delegating separation responsibility to the remote pilot under digital flight rules.
- Automation is also needed to enable the integration of the UA into traffic patterns and along the approach to the runway, particularly to support the remote pilot responsibility to space the UA behind other aircraft at non-towered airports. Such automation goes beyond detect-and-avoid capabilities in terms of perception and decision-making needs.
- Lastly, under LC2L conditions, procedures are needed to provide predictable UA behavior to the remote pilot and ATC. In the far-term, as UA operations increase in volume and extend to off-nominal conditions, UA automation will be needed to enable dynamic autonomous avoidance of hazards including weather and other traffic.

Novel solutions involving numerous automation technologies are needed to mitigate traffic and airspace management challenges, especially for realizing m:N operations and ensuring safety under LC2L conditions. The purpose of this document is to help understand alternatives and tradeoffs among potential solutions and provide a foundation for a cohesive PAAV concept that will be described and refined in subsequent concept versions.

1 Introduction

1.1 PAAV Subproject Objectives

The National Aeronautics and Space Administration's (NASA's) Pathfinding for Airspace with Autonomous Vehicles (PAAV) is a subproject of the Air Traffic Management - eXploration (ATM-X) project within the Airspace Operations and Safety Program (AOSP). PAAV's concept presents evolutionary paths forward to achieve highly scalable operations of large uncrewed aircraft systems (UAS) which will fly point-to-point between airports across the United States, where multiple uncrewed aircraft (UA) may be simultaneously controlled or supervised by a smaller number of remote pilots (RPs). This is part of the Regional Air Mobility concept [1].

The PAAV subproject aims to achieve its goal through the following four objectives:

- Produce a concept description, informed by industry and vetted with the FAA, that identifies needs and selected procedural and/or automation solutions for the integration of emerging UAS cargo operations into the National Airspace System (NAS) and examines necessary changes to existing roles and responsibilities between humans and automation.
- Identify functional requirements which address major barriers to routine UAS cargo operations.
- Develop technology prototype(s) needed for robust, safe, scalable, seamless, cost-effective, and equitable UAS cargo operations.
- Test and validate selected procedures and/or technology requirements, described in the concept, in a flight demonstration.

1.2 Background

The commercial air cargo market has been identified as a promising path for increasing autonomy of vehicles and ground support systems and is the most viable near-term business case for remotely piloted operations. By remotely piloting a UA, or flying the UA without a pilot onboard, numerous benefits to the industry have been postulated, including alleviation of a severe pilot shortage, increased utilization rates of aircraft, and more flexibility in crew management.

As demand for commercial air cargo is expected to grow, industry has indicated increased interest in utilizing remotely piloted large UA technologies for air cargo operations. The Federal Aviation Administration (FAA) forecasts that crewed large cargo jet aircraft fleets will more than double in size from 876 aircraft in 2021 to 1,959 aircraft in 2042 [2]. At the same time, the airline industry, especially regional airlines, has already been experiencing pilot shortages due to combined effects of various factors, such as the FAA's 1500-hour rule (i.e., a pilot must accrue 1,500 hours of flight time before qualifying for the Airline Transport Pilot certificate), more mid-career pilots switching to non-aviation careers, and more senior pilots accepting early retirements. Boeing predicts that 130,000 new pilots will be needed in the next twenty years (2021-2041) to fulfill the flight demands in North America [3]. Such demand will lead to competition among airlines for qualified pilots. Since pilots often prefer to work for major airlines, regional air operators are expected to face severe pilot shortages.

The industry hopes that remotely piloted UA can help fill the gap created by pilot shortages and respond to the market's demands by operating more flights with fewer pilots. In order for UA operations to alleviate the pilot shortage, UA must be able to fly in a manner compatible with the existing NAS structure and operations. The most expedient solution includes operations flying under instrument flight rules (IFR). UA operations must also be highly scalable to offset the additional cost of increased automation technologies being added to the aircraft and the supporting ground systems.

1.3 Scope

The initial PAAV focus is on UA operations at conventional airports (i.e., airports with runways) located within low complexity airspace (i.e., Class C, D, E, and G airspace). PAAV's initial research scope is regional UA cargo operations. For more specific definitions regarding the term "regional" and why regional cargo operations were chosen, see Section 2.1.1. High complexity airspace, such as Class B airspace, is currently outside of the scope of this work, though is expected to be included in future extensions of this work. Following the “crawl, walk, run” approach, PAAV will focus initially on lower complexity airspace. This lower complexity airspace is also where most regional cargo operations take place.

The PAAV concept scope includes turboprop, regional jet, and piston aircraft with special emphasis on the turboprop aircraft as it is currently the dominant engine type in the regional air cargo operations. Large jet aircraft, such as narrow- and wide-body jets, that typically operate out of large and complex airports, are initially outside of the scope of this work, but may be included in future extensions of this work to higher complexity airspace. Vertical takeoff and landing (VTOL) aircraft, including eVTOL and Part 107 operations of small UAS (sUAS) less than 55 pounds, are out of scope due to their shorter flight ranges. Consequently, the vertiports and other non-conventional airports exclusively supporting these types of vehicles are also outside the scope of this work. Turboprop aircraft which utilize novel propulsion technologies (e.g., electric, hydrogen) are included in the scope but with reduced emphasis initially. While this concept scope may, in the future, scale to include passenger transportation, there are additional elements that will need to be considered. At present, these additional elements unique to passenger transportation are outside the scope of this work.

1.4 Purpose of This Document

The purpose of this document is to present key challenges and preliminary conceptual solutions that resulted from the initial research activities of NASA's PAAV subproject. This initial version does not provide or suggest a single concept, but rather serves as a preparatory step toward the final PAAV concept that will be formulated in later versions. This document also helps identify further research focus areas. This further research will examine tradeoffs between the alternative solutions presented in this document, and derive a final concept with concept elements drawn from these tradeoffs. Some of the contents of the present document reflect initial findings from various PAAV team activities performed in the last two years, including four tabletop exercises, a human-in-the-loop simulation study, a numerical simulation study, functional allocation study, flight data analysis, and consultations with subject matter experts (SMEs). Details of some of these activities are summarized in Appendix A.

1.5 Terms

In this document, the following terms are used. The list is limited to only those that often cause confusion or questions.

- **Uncrewed Aircraft (UA):** In this document, UA refers to aircraft where no human pilot is onboard. The term "uncrewed," rather than "unmanned," is consistent with emerging usage and will be used in this document. UA could be remotely piloted or fully autonomous. However, in this document, the UA is, in nominal operations, always remotely piloted. However, there are off-nominal situations in which the UA will operate automatically or autonomously (i.e., without a remote pilot). These situations and terms will be explicitly noted so as to avoid any confusion.
- **Uncrewed Aircraft System (UAS):** UAS refers to the UA and all the other systems that support the UA operation, including ground systems (e.g., the ground control station), communication systems, and operators. In the wider UA community, the terms remotely piloted aircraft (RPA) and remotely piloted aircraft systems (RPAS) are often used in place of UA and UAS, respectively, to specifically refer to aircraft

with a remote pilot. However, in this document, UA and UAS terms are used following the current convention of the FAA and RTCA.

- **Remote Pilot (RP):** The RP is the human operator on the ground who commands and controls the UA. Note that some in the wider UA community may call this operator the Ground System Operator (GSO).
- **Remote Pilot in Command (RPIC):** The pilot in command (PIC) "has final authority and responsibility for the operation and safety of the flight" (14 CFR §1.1), but does not necessarily have to be the pilot flying. The RP who is the PIC of the UA is specifically referred to as the remote pilot in command (RPIC). The RPIC does not have to be the RP controlling the UA. In this document, RP is used in most places instead of RPIC unless the PIC authority and responsibility are necessary (e.g., flight planning).
- **Ground Control Station (GCS):** The ground control station is the workstation, located on the ground, from which the RP controls the UA.
- **Command and Control (C2) link system:** The C2 link system supports the command, control, and communication functions of the UAS operation. This document calls the system the C2 link system, C2 link, or C2, aligning with the RTCA DO-377A conventions [4]. (The RTCA DO-362A [5], on the other hand, refers to the system as Control and Non-Payload Communication (CNPC) Link System.) Communication includes both voice and data. The C2 and communications architecture in this document includes the C2 link system and the additional communication network connecting the UA, GCSs, air traffic control, and third-party service providers supporting the UAS operations.
- **National Airspace System (NAS):** The NAS is a network of U.S. airspace, including both controlled and uncontrolled (i.e., Class G) airspace, along with associated facilities and services.
- **Uncontrolled airspace:** Uncontrolled airspace means that an air traffic controller (ATC) has neither authority nor responsibility to control air traffic flying in the airspace. However, the airspace is still part of the NAS.
- **Towered/Non-Towered Airport:** The towered or non-towered airport is an airport with or without, respectively, an operating airport traffic control tower (ATCT). Note that the classification is independent from the controlled vs. uncontrolled classification of airspace. For instance, either type of airport could be located in controlled (e.g., Class E) or uncontrolled (Class G) airspace. Also note that the "non-towered" designation does not necessarily mean absence of a physical tower. For example, an airport may have a part-time ATCT which does not operate at night. In that case, the airport becomes a non-towered airport at night. A non-towered airport may also be referred to as a Common Traffic Advisory Frequency (CTAF) environment in this document.
- **Special Use Airspace (SUA):** Some portions of controlled and uncontrolled airspace are designated as Special Use Airspace (e.g., Military Operation Areas or MOAs) or other airspace areas (e.g., visual flight rules corridors). These airspace areas are still under the purview of NAS rules even if the FAA is not the sole regulator (e.g., military controls the MOAs while the MOAs are active) (Section 3-1 of AIM [6]).
- **Automation:** Automation means that the system performs specific tasks following predefined procedures.
- **Autonomy:** Autonomy means that the system can independently make its own decisions, even under unforeseen circumstances, without human intervention. Autonomy can be achieved through a higher level of automation (e.g., machine learning).

2 Operational Context

To set the scope of the PAAV concept development, this section describes the expected operational context of PAAV including the flight mission, the baseline UAS components (i.e., UA, GCS, C2 link system, DAA, and the operators), nominal end-to-end operation, m:N operations (i.e., "m" RPs per "N" aircraft), and off-nominal operation with focus on lost C2 link.

2.1 Mission Description

2.1.1 Flight Mission

A NASA-funded automated air cargo operations market research study by Logistics Management Institute (LMI) [7] identified four different uses of UA, i.e., *use cases*. These are heavy/long range, heavy/medium range, regional, and light as defined in Table 1.

Table 1. LMI Automated Air Cargo Use Cases

LMI Use Case	Mission Range (nmi)	Payload (tons)	Speed (knots)
Heavy/Long Range	> 3,000	> 40	400-500
Heavy/Medium Range	500-3,000	> 10	350-500
Regional	75-1,000	1-10	150-300
Light	< 250	0.025-1	< 200

LMI reported that the regional use case was found to be most promising in terms of opportunity to integrate UA into the NAS in the next 20 years. The study reasoned that regional air cargo use cases, which are typically experiencing aging fleet, high pilot cost as a share of the total operational costs, and crew inefficiency during long layovers at outstations, as well as the ongoing pilot shortage, would provide increased opportunity and support for UA integration.

Thus, the flight mission that PAAV will focus on for UAS integration is the regional air cargo transportation use case shown in Table 1, i.e., a remotely piloted turboprop or regional jet aircraft with a payload capacity of 1 to 10 tons which is flown along a typical flight length estimated to be 75-1,000 nautical miles (nmi). These flights may be operating under 14 CFR Part 121 or Part 135. Payload and distance thresholds in Table 1 are applied initially, but these thresholds may be adjusted later. As described in the Scope section (Section 1.3), departures and arrivals occur at conventional airports contained within Class C, D, E, or G airspace. Class B airports, vertiports, and other non-conventional airfields are outside of the scope of this concept. In the PAAV concept, fixed-wing UA flights will take off and land using conventional runways, and will merge with other IFR and visual flight rules (VFR) flights.

2.1.2 Certificate of Waiver or Authorization (COA)

Currently, Certificates of Waiver or Authorization (COAs) are used to permit UAS operated by persons, public agencies, organizations, and commercial entities flying in the NAS for specific UA activities. A COA provides provisions, limitations, and special procedures to manage the risk of the operation and permits the UAS to operate within the area authorized in the approved COA. Safety procedures that a COA requires may include use of visual observers, chase aircraft, or new technologies. A COA may also specify the requirements for air traffic control coordination, communication, flight planning, emergency/contingency procedures, and other procedures for the UAS flight. The COA application process often takes months to complete, and there is desire in industry to eliminate this process or, at least, initially reduce the COA process through standardization. For example, standardizing the UAS emergency/contingency procedures would help expedite the COA application process.

2.1.3 IFR Flight Plan

In addition to a COA, flight plans are typically filed for large UAS operations, just like in conventional Part 91 crewed aircraft IFR flight operations. It is envisioned for the end state of this concept that the flight plan is used as a method to inform the FAA of the unique specifics of UAS operations, such as planned contingency procedures. The concept is sometimes called "file-and-fly." Standardized flight plan format for contingency procedures may be especially helpful for the information to be submitted in a relatively compact format as a part of the flight plan and readily accessible to ATC when needed. This may eventually help UAS operator avoid the need to go through the COA process for each flight.

Another consideration for the UA flight plan is that, unlike a conventional flight plan which contains waypoints but still has discontinuities to be filled by an ATC through vectoring, the UA's entire IFR flight plan must be predefined and remain "end-to-end complete" throughout the flight. Any discontinuities in a flight plan would lead to incomplete flight intent for automatic guidance, navigation, and control functions, which complicates lost C2 link (LC2L) procedures, especially with open vectoring (i.e., vectoring without specifically instructed point at which the UA must return to the course). When the ATC issues instructions to the UA that contain open vectoring, the flight plan may need to be updated with deterministic points specifying where the maneuver starts and where the UA rejoins the original route. Some standardization for this process for the UA flight plans may be helpful. To be "end-to-end complete," the flight plan should include the runway at the destination airport (currently being proposed in RTCA SC-228), as well as defined LC2L procedures. The LC2L procedures should be updated as the flight plan is amended.

The UA flight plan will be initially an IFR flight plan regardless of the instrument or visual meteorological conditions (IMC or VMC, respectively). IFR flight plans may contain the Standard Terminal Arrival Routes (STARs), Instrument Approach Procedures (IAPs)—including their missed approach procedures—and Standard Instrument Departures (SIDs). In addition, UA-specific equivalents to these procedures could be published and utilized. UA operations will interact with ATC in accordance with IFR procedures.

2.2 Uncrewed Aircraft System (UAS) and Other Agents

This section describes the major, or *baseline*, UAS components. These are the uncrewed aircraft (UA), the ground control station (GCS), the C2 link system, the remote pilot (RP), and the detect and avoid (DAA) system. Note that there are more UAS subsystems not included here (such as ground-based surveillance systems, flight management systems, etc.).

2.2.1 Uncrewed Aircraft (UA)

Representative aircraft types for this business case include the following:

- Cessna 208 Caravan and 408 SkyCourier
- ATR 42 and 72
- Beechcraft 1900, King Air, and Model 99
- Embraer ERJ 135 and 145

These aircraft types are not all-inclusive and future remotely piloted cargo operations may use new aircraft entrants. It is likely that, at least initially, some aircraft currently used for air cargo operations will be retrofitted to enable remotely piloted air cargo operations.

It is expected that the UA will be equipped sufficiently for the planned IFR flight operation in a similar manner to crewed aircraft. The UA is also expected to be equipped with advanced communication and surveillance systems, such as Automatic Dependent Surveillance-Broadcast (ADS-B) In and Out, as well as a Mode S transponder, regardless of the equipage requirements for the airspace where the UA operates. Although the UA is not carrying passengers, the UA may be equipped with advanced safety systems required for the Part 135 passenger-carrying operations, such as Ground Proximity Warning System (GPWS) and airborne thunderstorm detection equipment (14 CFR §135.154, 135.173) to support its automated hazard avoidance capabilities. The UAS is expected to have a flight management system (FMS) capability with components onboard and on ground.

2.2.2 Command and Control (C2) Link System

Figure 1 shows a general operational view of a UAS that includes two C2 link systems to connect the RP with the UA for vehicle command and control as well as for communications with ATC. The two types of C2 link systems illustrated are a terrestrial link system that relies on radio frequency (RF) line-of-sight between its ground radio stations (GRSs) and the UA, and a satellite communication (SATCOM) link system that communicates the C2 data to UA flying within its system spot beam coverage area(s). In operation, this configuration of the C2 link system would provide service from either system, at any one time, to provide contiguous C2 link system connectivity for complete end-to-end UA flight route operations. This service condition would be dependent upon which system can provide the best available performance. The configuration shown also uses a relay-through-the-UA arrangement for RP-ATC voice dialog that relies on the C2 link system and legacy very high frequency (VHF) ATC analog radio systems. Operating characteristics and limitations of each C2 link system for performance, air-route coverage due to infrastructure, coverage range, or terrain limitations would be considered in providing the C2 link system in use. Minimum aviation system performance standards (MASPS) (DO-377A [4]) and minimum operational performance standards (MOPS) (DO-362A [5]) for the C2 link system are published by RTCA Special Committee 228 (SC-228).

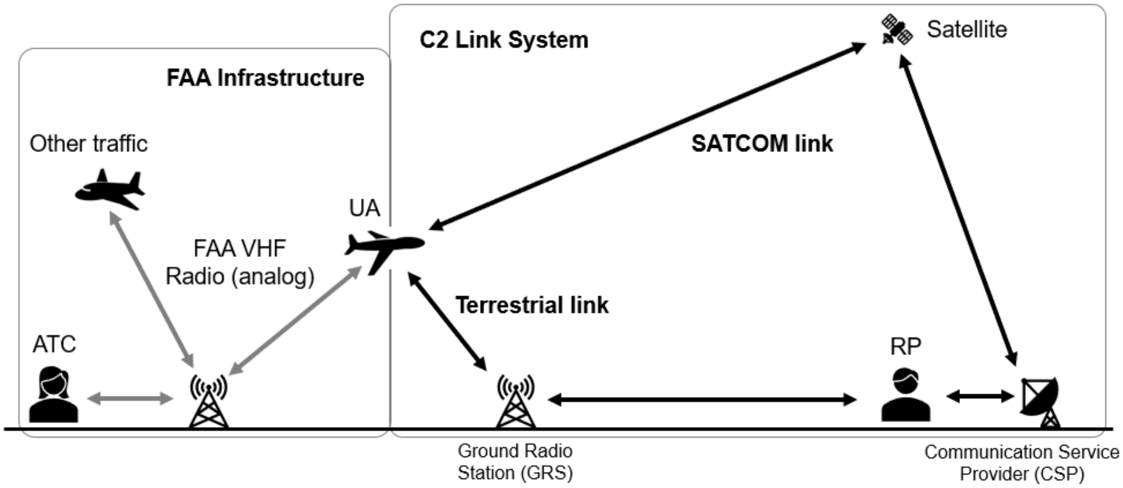


Figure 1. C2 Link System

Primary operations carried out by the C2 link system envisioned today are as follows:

1. RP commanding of the UA for aviation of the aircraft.
2. Return of UA state data and subsystem telemetry for RP monitoring.
3. Transmission of two-way voice and digital messaging between the RP and ATC.
4. Transmission of surveillance data between the UA and GCS.

In addition, with advancement of UA capabilities envisioned for the future, the C2 link system may also convey low- or high-resolution video data from cameras onboard the aircraft. The video camera feeds may be helpful for taxi, takeoff, and landing operations; conflict detection and avoidance; and any other potential VFR-like capabilities to enable safer and more efficient remote piloting of UA. Note that the transmission of high-resolution video data requires high bandwidth and is yet to be supported by the current state-of-the-art C2 link system technologies. Limited low-frame-rate video has been supported for takeoff and landing.

2.2.3 Detect and Avoid (DAA)

Regulations require all aircraft flying in the NAS to "*see-and-avoid* other aircraft" and "give way to that aircraft (that has the right-of-way) and (they) may not pass over, under or ahead of it unless *well clear*" (14 CFR §91.113). Since UA do not have a pilot onboard, they require a digital means of providing an equivalent level of safety as see-and-avoid. *Well clear* can be defined as sufficient distance from another aircraft so as not to create a collision hazard (see 14 CFR §91.111), but a specific well clear distance is undefined and left open to the subjective judgement by the pilot onboard.

To address the gap, RTCA SC-228 developed a risk-based DAA Well Clear (DWC) definition for UAS operations and performance standards for alerts and guidance of the DAA system (DO-365B [8]). The FAA technical standard orders require that DAA systems meet the RTCA standards (FAA TSO-C211 [9]).

The RTCA DO-365B specifies the three DWC threshold parameter sets shown in Table 2, depending on the intruder type (cooperative vs. non-cooperative, i.e., aircraft that does not have a functioning transponder or ADS-B) and the airspace where the intruder is located (en route vs. terminal). Note that *terminal* airspace in the DAA context is defined as the region within 4 to 5 nmi from the center of the runway, not Terminal Radar Approach Control (TRACON) airspaces. The parameters include modified tau (τ_{mod}, a parameter related to time to closest point of approach), horizontal miss distance (HMD), and vertical separation threshold (h).

Table 2. DAA Well Clear (DWC) Thresholds

DWC	τ_{mod} (seconds)	HMD (ft)	h (ft)
En Route Cooperative	35	4,000	450
En Route Non-Cooperative	0	2,200	450
Terminal	0	1,500	450

DO-365B classifies DAA systems into eight classes depending on the airborne, terminal, and ground alerting and guidance capabilities. Based on the airborne capabilities, a DAA system is classified into the following three classes:

- Class 1 (DAA Remain Well Clear, or RWC)
- Class 2 (Traffic Alert and Collision Avoidance System II, or TCAS II; Resolution Advisory, or RA; and DAA RWC)
- Class 3 (Airborne Collision Avoidance System for Unmanned Aircraft, or ACAS Xu)

The DAA system utilizes the signals from active surveillance or TCAS II, ADS-B In, air-to-air radar (ATAR), electro-optical/infrared (EO/IR) systems, and Ground-Based Surveillance System (GBSS) to generate traffic-avoidance alerting and guidance for the RP. Note that the DAA system currently does not require video camera inputs. DAA alerting and guidance are currently limited to flights operating between 400 ft above ground level (AGL) and Flight Level 180, and not applicable to UA operating in the traffic pattern (see Section 4.3) or on the surface.

2.2.4 Personnel and Their Roles and Responsibilities

The remote pilot (RP) controls the UA from a GCS using a C2 link system. The RP also communicates with ATC via the C2 link system. Multiple RPs may be working as a team to operate a single UA or multiple UA. In that case, roles and responsibilities among the RPs must be well-defined and any transition of these roles between RPs must be clearly communicated among the RP team members, similar to the positive transfer of control within the cockpit of crewed aircraft. The allocation of roles and responsibilities may be similar to those of crewed aircraft operations (e.g., pilot-flying vs. pilot-monitoring) or unique to UA flights (e.g., pilot-flying vs. pilot-communicating). Like in crewed aircraft flight operations, the RP who is the remote pilot in command (RPIC) is legally responsible for the UA flight. A single UA could be handed off from one RP, or team of RPs, to another/others in mid-flight. The RP team members can be collocated or distributed over multiple locations. The training, certification, and licensing for RPs will likely be different (ideally less intensive to support scalability) from those of the conventional crewed aircraft pilots.

The UA flight may have a dispatcher, similar to current-day cargo operations. The dispatcher could assist the RPIC for flight planning, monitor the progress of the flight, and issue any necessary information for the safety of the flight. The dispatcher would share the legal responsibility for the flight with the RPIC, just like a dispatcher for crewed aircraft operations. The dispatcher may or may not be collocated with the RPs.

The RP team may also have a supervisor who helps with coordination, similar to how an air traffic control supervisor coordinates ATCs. The supervisor could potentially fill in for an RP position for a short period of time to offer relief if the supervisor is qualified to do so. The supervisor may or may not be collocated with the RPs.

When the RPIC is not located at the departure airport, the ground crew at the airport would conduct all the necessary physical preflight inspections and communicate appropriately with the RPIC so the RPIC can make the go/no-go decision. The ground crew performs all the physical preflight tasks normally performed by a crewed flight's pilot, which may include starting the engines, until the UA is connected with the C2 link system. The ground crew may have even more extended responsibilities to monitor the UA's taxi and takeoff operations to ensure safety. The ground crew for UA operations would have increased responsibility than those of crewed aircraft operations, and thus additional training and new certification processes are likely required.

ATC should be able to treat the UA flight in a similar manner to conventional crewed aircraft in most cases. However, their roles and responsibilities may still need to be adjusted to accommodate the uniqueness of the UA flight operations. For example, the ATC should be aware of some minor differences, such as delays both in RP voice transmissions and responses to maneuvering instructions due to delays in the C2 link system, the inability of the RP to report having other traffic or airport visually in sight (alternative phraseologies for the UA have been recommend by RTCA SC-228, e.g., "traffic detected" instead of "traffic in sight" [8]), and the UAS's limitations, such as the inability to accept a visual approach clearance. The ATC would need to be trained for LC2L events, including how to find the filed LC2L procedure descriptions. ATC would have the option to reject the RP's request to enter the ATC's airspace if their workload is high (in the same manner that they may for crewed aircraft).

Third-party service providers may be necessary to support some of the proposed air cargo operations, e.g., flight route optimization (see Section 5.5), communication, ground-based surveillance, and UA corridor control operation (Section 5.3) services. Their roles and responsibilities will be identified in later iterations of the concept documents.

2.2.5 Ground Control Station (GCS)

The ground control station (GCS) is the workstation on the ground that the RP uses to control a single or multiple UA and communicate with ATC. The GCS is not simply a flight deck on the ground. The RP needs to manage additional information unique to the UA operations, such as DAA alerting and guidance, surveillance information, state of the C2 link system connectivity, and states of various UAS automation. The GCS may use the regular computer interfaces, such as keyboard, mouse, and touch screen, rather than the conventional flight deck controls like yoke, joystick, foot pedals, and control panel interfaces (e.g., switches, buttons, and knobs). Unlike the pilots onboard, the RPs on ground have access to extensive traffic, weather, and airspace information as well as ability to use land lines to talk with the ATC, maintenance, weather experts, etc., even in mid-flight.

The design of the GCS will likely influence how effectively the remote pilot can manage and respond to ATC radio communications. There is a need for standardized performance-based methods of, for instance, measuring the RP's response time to ATC clearances. The GCS human-machine interface also needs to be designed to minimize errors and provide the RP with the information they need to effectively monitor the flight at any level of automation requiring difference degrees of human involvement. However, there is currently no standard for GCS user interface design for UAS. There have been some human factors guidelines for UAS GCS designs published by the European Organisation for Civil Aviation Equipment (EUROCAE) [10] and NASA's UAS in the NAS project [11]. For the DAA alerting and guidance information, RTCA DO-365B [8] specifies how the information should be visually and aurally presented to the RP.

2.3 Nominal m:N Operations

A key objective of the PAAV concept is developing solutions to allow fewer operators (m) to control more UA (N) over most phases of flight, referred to as "m:N" (read as "m-to-N") operations. Industry stakeholders have pointed to the potential of m:N as a rationale for relying on uncrewed aircraft to drive down future operating costs associated with pilot staffing and aircraft utilization. Ability to operate more flights with fewer pilots may also enable more point-to-point operations often preferred by customers of air cargo operators over conventional hub-and-spoke operations.

2.4 Lost C2 Link (LC2L) Operations

A LC2L communication between the RP and the UA can result in one or all of the following conditions:

- RP can no longer issue flight commands to the UA (lost uplink).
- RP can no longer directly determine the flight state of the UA (lost downlink).
- Communication between the RP and local ATC via the UA's onboard very high frequency (VHF) radio(s) is disrupted.
- Surveillance information is no longer provided to the GCS.

Contingency management for LC2L must be considered for every phase of flight of the UA operation, since LC2L can occur during pre- or post-flight operations such as taxi, as well as during in-flight operations such as takeoff, departure, cruise, arrival, approach, and landing.

Actual operational experience with LC2L is to-date largely derived from military operations. Several useful references exist which describe LC2L contingency management procedures for both domestic military and non-military commercial applications, such as the automated cargo operations proposed by PAAV. These references include the following:

- FAA internal report, "UAS NAS Integration: Lost Link Procedures Concept Document," prepared by Cavan Solutions in June 2020, describes a framework for a timer-based lost link contingency management protocol.

- UAS National Airspace System Flight Operations Standard Procedures (UNFO SP), formulated in July 2015, includes proposed LC2L procedures, describes roles and responsibilities for UA, RP and ATC during LC2L, and includes proposed charting requirements.

- RTCA DO-377A [4] includes LC2L definitions, operational assumptions and system requirements for designing UA systems with LC2L mitigation.

- EUROCAE ED-281 [12] describes system requirements for a generic Automation and Emergency Recovery (A&ER) capability including LC2L.

- Notes from the International Civil Aviation Organization's (ICAO's) 16th Meeting of the Remotely Piloted Aircraft Systems Panel on the Progress on Lost C2 Link and DAA Procedures, RPASP/16-WP/15, includes draft modifications to ICAO Annex 2 'Rules of the Air' to include LC2L provisions and 'Procedures for Air Navigation Services' to include provisions for DAA integration.

3 Near-Term and Far-Term Assumptions

To guide the evolutionary approach of the PAAV concept development, a number of near-term and far-term assumptions were made (Table 3). Near-term assumptions refer to what is expected by industry stakeholders (e.g., RTCA) to be feasible for the initial introduction of these operations into the NAS (DO-304A [13]). Far-term assumptions reflect the end state that was identified by the LMI market study, which emphasized industry desire to reach m:N operations through increased levels of automation and supporting procedures and technologies. The bold text in Table 3 highlights the differences between the near-term and far-term assumptions.

Table 3. Assumptions

Category	Near-Term	Far-Term
Operational Regulation Type	UA have airworthiness certificates, enabling operation under **Part 135**.	UA have airworthiness certificates, enabling operation under **14 CFR more generally**.
Communication, Navigation and Surveillance (CNS)	CNS will use conventional methods such as **voice communication between ATC and the RP** using the UA voice relay capability, and **conventional surveillance and navigation capabilities** (leveraging satellite and digital technologies as feasible).	CNS will use advanced methods including more **digital communication between ATC and the RP**, leveraging **satellite, cellular, and High Altitude Relay System (HARS)** technologies as feasible, and more advanced **vehicle-to-vehicle communications.**
Airspace Complexity	UA operations will be limited to **low complexity airspace**, such as Classes C, D, E, and G, serving markets around small **regional airports.**	UA operations are expanded to **more complex airspace and major airports (e.g., Class B airports).**
Flight Rules	UA will fly **exclusively under IFR.**	UA will fly using IFR or tailored flight rules that facilitate increasingly autonomous operations, including the ability to **accept visual approach clearances** (e.g., Digital Flight Rules [14]).
Separation Services	Separation services are provided by the **FAA in controlled airspace** and the IFR UA will mix with VFR traffic in controlled and uncontrolled airspace, using existing flight rules and conventional means and processes (e.g., advisory services, CTAF).	Separation services are provided according to the **Info-Centric NAS and Sky for All visions** [15], including, for example, more **automation** and **third-party services.**
UA Equipage and Capabilities	UA are equipped with C2 capabilities and DAA functions for which standards have been largely developed.	UA are equipped with C2 capabilities and DAA functions, including **advanced terrain and weather avoidance capabilities**.
m:N Ratio	UA will be operated remotely with **one or more operators per UA at any one time**.	UA are operated remotely with **multiple (m) operators per multiple (N, where N > m) UA**, via high level of automation with human operators acting as supervisors.
Contingency Management	Contingency management procedures are **prescribed and coordinated.**	Contingency management procedures are **automated** with **well-defined human operator roles.**

4 Operational Challenges

Based on the results from the tabletop exercises (Appendix A.1), a number of challenges were identified. Figure 2 illustrates some of these identified challenges. The solid lines depict the nominal paths, whereas the dashed lines are off-nominal paths.

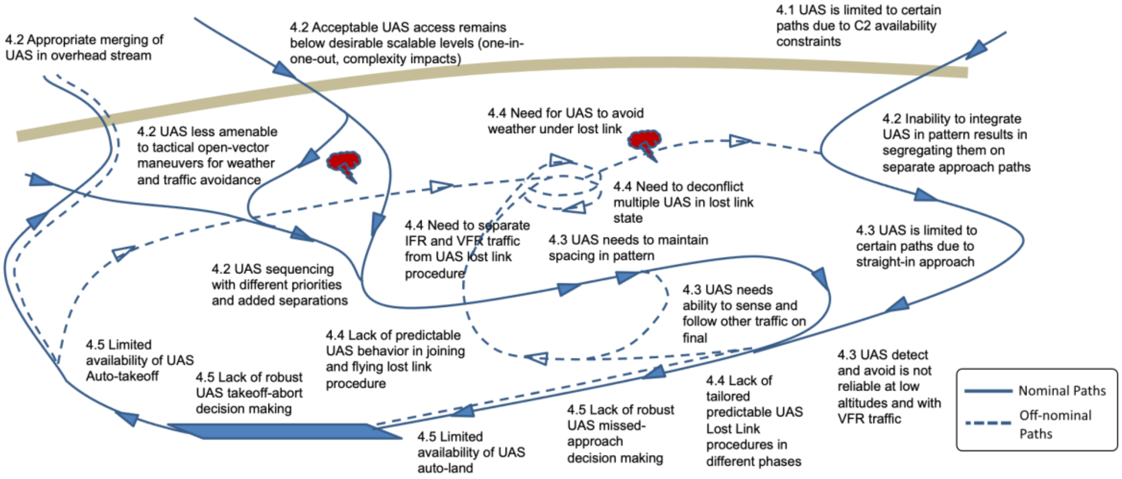


Figure 2. Key Functional Challenges

The identified challenges can be grouped into the following seven areas. The challenges shown in Figure 2 were also marked with the corresponding section numbers. (Not all challenge areas are depicted in Figure 2.) The challenges are grouped from the ATC's viewpoints to address the issues of airspace integration of the UA flight operations, rather than from the viewpoints of pilot's operational sequence (e.g., taxi, takeoff, departure, cruise, approach, and landing), although some challenges may touch upon the UA's capabilities (e.g., taxi, takeoff, and landing).

- Flight route planning (Section 4.1)
- Separation and flow management (Section 4.2)
- Traffic pattern integration (Section 4.3)
- Contingency management (Section 4.4)
- Taxi, takeoff, and landing (Section 4.5)
- m:N operations (Section 4.6)
- Communications operational challenges (Section 4.7)

This above list of challenges is not comprehensive and will be updated in future versions of this document as more research is conducted.

4.1 Flight Route Planning

Predeparture flight route planning for a UA flight may need to take some unique factors into consideration in addition to those usually considered in the crewed aircraft flights' route planning. For example, not all airports or runways may be able to accommodate UA flights. The C2 link coverage along the route—including the link signal reliability and backup C2 link signal availability—as well as options for LC2L contingency procedures may also need to be considered. For additional safety buffer for the UA flight in the NAS, it may be more prudent for the UA operator to select routes that fly through less congested airspaces that have fewer chances of airborne reroutes for weather or other airspace restrictions. Third-party services may be used for some parts of the UA flight route planning.

4.2 Separation and Flow Management

Safety of airspace operations is achieved by maintaining a safe distance between aircraft at all times, which is accomplished through layers of flow management and separation services. Flow management manages traffic flows in a manner that prevents traffic demand from exceeding the allowable capacity of resources such as airspace regions, airports, and specific runways, through programs such as flight planning, route optimizations, and metering. (In this document, strategic separation is maintained primarily by traffic flow management, thus these words are used interchangeably.) If flow management is insufficient, tactical separation ensures the safe distance between aircraft through actions such as vectoring, altitude changes, and speed changes. For aircraft operating under IFR within controlled airspace, ATC is responsible for separation and flow management. For aircraft operating under VFR or within uncontrolled airspace, the pilot is solely responsible for ensuring safe separation and complying with any relevant flow restrictions by adhering to rules such as operating only in visual meteorological conditions (VMC) and relying on the see-and-avoid principle.

UA operations pose many challenges to both strategic and tactical separation. Figure 2 above depicts some of these challenges based on findings of the PAAV team's research activities, particularly the tabletop exercises (Appendix A.1).

There are a number of challenges associated with the strategic separation (i.e., flow management) of UA operations:

- For example, as indicated in Figure 2 above, when UA lands at a non-towered airport inside a non-radar coverage airspace as an IFR flight, only one IFR flight can be allowed inside at a time, which does not provide the scalability desired for these operations.
- At towered airports, more than one IFR aircraft can be admitted simultaneously; however, the acceptable number of UA operations needs to be determined based on their impacts on the complexity for both ATC and pilots, which are not yet established.
- Since these UA cargo operations are expected to increase at small regional airports, flow management methods at these airports need to account for their volume and particular characteristics. Current flow management methods which are deployed and common at larger airports, such as metering and ground delay, may need to be extended to small airports with increased demand for cargo operations, with tailoring to account for the characteristics described in the next bullet.
- There are a number of reasons UA operations may need special accommodation in terms of what airspace, routes, departure procedures, approach procedures, and airports they may be able to use. First, they need a reliable and robust C2 link. This requirement may limit access to some airports, as well as some routes in the en route phase and in the terminal area. Secondly, current standards assume the UA will only fly straight-in approaches. The UA may also have different capabilities, for example, in flying optimized profile descents or meeting time-of-arrival constraints.

There are also a number of challenges associated with the tactical separation of UA operations:

- In controlled airspace and particularly in the terminal area, ATC resorts to issuing vectors when resolving conflicts due to traffic and weather hazards. UA flights are challenged when responding to vectoring instructions from ATC as the UA's contingency plans may need to be updated each time the UA deviates.
- There are challenges that must be considered for DAA to provide an equivalent level of safety with what is achieved by the human pilot's see-and-avoid capabilities in a variety of visual conditions. For instance, the ATAR that DAA uses is still challenged at low altitudes by ground clutter. The GBSS may help to alleviate the ground clutter issues, but is ineffective during a LC2L condition. Additionally, GBSS cost of implementation may be prohibitive. Detection of non-cooperative traffic with a small radar cross-section may also be a challenge for DAA.
- Interoperability among separation alerts and guidance provided by ATC, DAA, and TCAS may be another potential challenge.

Some findings of the PAAV team's research activities corroborated these challenges. At the tabletop exercises (Appendix A.1), ATCs indicated that the use of vectors is critical to the flexibility needed in the terminal area traffic management. Latencies in communication due to the C2 link communication via UA as a relay can force ATCs to add buffers to the separation criteria. A human-in-the-loop (HITL) simulation (Appendix A.3, or [16]) demonstrated that a longer UA voice delay increased instances of radio step-ons (i.e., simultaneous radio transmissions by multiple speakers). Step-ons are a concern because they may prevent the RP from talking with the ATC when needed, and/or require re-transmission of the stepped-on messages that will make the radio frequency even more congested. Furthermore, a fast-time numerical simulation study (Appendix A.4, or [17]) indicated that a UA maneuver execution delay of 30 seconds or more and a resolution message drop probability of greater than 0.2 could result in increased losses of separation and hence compromised safety.

4.3 Traffic Pattern Integration

The traffic pattern is an essential component of the NAS infrastructure needed to ensure safe, orderly, and expeditious operations in the airport environment. The traffic pattern provides procedures for pilots to follow during takeoffs, departures, approaches, and landings, and is established based on local airport conditions. Figure 3 identifies the legs of the traffic pattern, including departure, upwind, crosswind, downwind, base, and final approach (AIM [6]). This figure shows the default left-hand pattern; a mirrored image is appropriate for right-hand patterns.

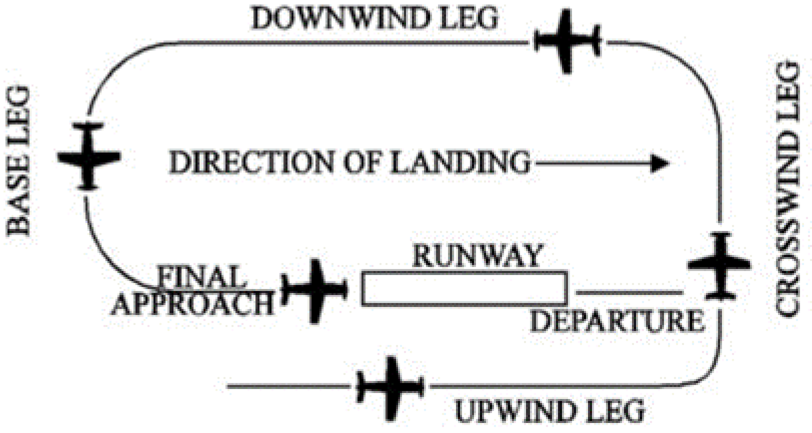


Figure 3. Traffic Pattern Components

The typical behavior within the traffic pattern includes a standard pattern altitude to join the downwind leg. Pattern altitude is maintained throughout the downwind leg, until the aircraft is abeam the numbers of the runway intended for landing, at which point the aircraft reduces power and begins a steady descent through the base leg until intercepting the final approach path and completing the landing. If a landing is not possible for any reason (e.g., runway occupied, unstable approach), the aircraft is permitted to perform a go-around. In this case, the aircraft will fly runway heading and turn to the crosswind leg beyond the departure end of the runway within 300 ft of pattern altitude, if not already at pattern altitude. Depending on the scenario (e.g., a departing aircraft), it may be prudent for the aircraft to side-step the runway and join the upwind leg before turning to the crosswind leg.

Figure 4 shows a variety of entry methods used to join an airport traffic pattern. The primary standard methods of entry include the following:

- 45 degree Entry – the preferred entry method for aircraft approaching the runway from the side of the traffic pattern involves entering the pattern at a 45-degree angle to the downwind leg, joining the downwind midfield.
- Midfield Entry – for aircraft approaching the runway from the opposite side of the traffic pattern, the preferred traffic pattern entry method involves the aircraft overflying the airport at least 500 ft above pattern altitude and (for a left pattern) performing a right teardrop turn to enter at 45 degrees to the downwind leg at midfield.
  - An alternative midfield entry shown in Figure 4 and discussed in the AIM is to enter on a midfield crosswind at pattern altitude and turn downwind. This offers a more expedited route to land but should not be used if the pattern is busy.
- Direct Base Entry – the aircraft bypasses the downwind leg and joins the traffic pattern in the base leg orthogonal to the intended landing runway.
- Straight-in Approach – the aircraft bypasses most of the traffic pattern, joining an extended final approach.

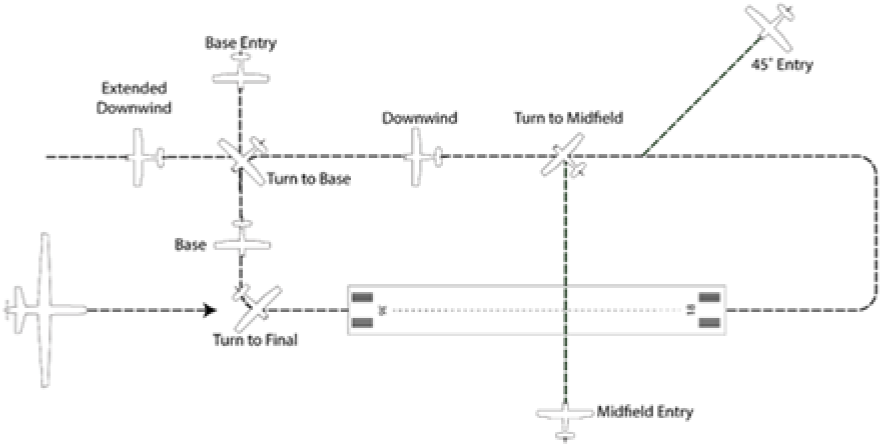


Figure 4. Typical Traffic Pattern Entries

One benefit of the traffic pattern is the improved efficiency it enables. Without the ability to fly the traffic pattern, the UA will be restricted to fly an Instrument Approach Procedure (IAP). Some IAPs designate initial approach fixes as far out as 20 nmi from the runway. It is easy to envision a scenario in which aircraft is flying from the opposite direction and must fly 20 nmi past the airport just to turn around in order to follow the published IAP. Further, the published missed approach procedures (MAPs) may define a hold point that is 10-20 nmi from the airport. In this case, it is possible to envision a scenario in which a UA must fly 80 nmi further than would be needed if the UA was not restricted to the IAP/MAP and able to approach the airport more directly, remaining within the airport environment if unable to land immediately.

While the traffic pattern is used at both towered and non-towered airports, the local controller at towered airports may use whatever means necessary to sequence and space aircraft. Often, the local controllers use the traffic pattern structure but specify aircraft maneuvers necessary to maintain spacing. Typical controller instructions for sequencing and spacing include the following: 1) having the arriving aircraft enter the traffic pattern via other than the 45 degree entry, 2) extending the downwind leg, 3) having the aircraft increase or decrease speed, or 4) requesting an aircraft perform a 360 degree turn for spacing.

In addition to looking out for other aircraft, pilots listening to the tower frequency at towered airports, or local CTAF at non-towered airports, develop situation awareness based on the radio calls issued by other aircraft. Although RPs will be able to develop situation awareness based on radio calls while the C2 link is nominal, a traffic pattern integration (TPI) tool may not have benefit of this information and will need to infer traffic intent based on state data.

This may prove particularly challenging at non-towered airports since pilots don't always fly the recommended traffic pattern or broadcast their intentions on the CTAF.

The DAA Well Clear (DWC) definition for the terminal environment is designed to allow DAA to remain active while the UA is on a straight-in approach without causing nuisance alerts for traffic on the downwind leg of the traffic pattern. This allowance results in the DWC definition being much smaller than the spacing required to safely follow traffic in the pattern. DAA is designed to keep the UA well clear of other aircraft, but a capability other than DAA is required to enable the RP or automation to properly space on traffic, regardless of whether the UA is on a straight-in approach or entering and flying the traffic pattern.

One impediment to the integration of UA in the traffic pattern is the inability to accept a visual approach clearance. During IFR flights conducted in VMC, it is common practice for a pilot to either cancel IFR while airborne or accept a visual clearance, enabling the pilot to deviate from the published IAP and join the traffic pattern using a standardized entry method, and leverage reduced visual separation minima. In these scenarios, the pilot assumes the responsibility for visual separation from traffic and obstacles or terrain which was previously provided by ATC. Since the current operational assumptions defined in DO-365B restrict UA approaches to IFR operations with "straight-in" approaches (A.2.1.1 in DO-365B [8]), cancelling an IFR flight plan is not an option to enable traffic pattern integration; therefore, the ability to accept an ATC clearance akin to the current visual approach clearance is needed for UA to fly the traffic pattern.

4.4 Contingency Management

There are several contingencies that are unique to UA operations with varying levels of severity including lost C2 link, lost DAA, and lost radio communication. While some off-nominal events may constitute an emergency based on the impact to the airspace and associated reduction in safety, there are other events likely to occur that may be procedurally mitigated before an emergency is created.

4.4.1 Lost C2 Link

Lost C2 link is expected to be a non-emergency event due to standardized procedures that provide for predictable UA behavior during a LC2L event. Discussions during tabletop exercises (Appendix A.1) indicated that the main challenge for UA contingency management is to provide predictability to both the UA operators and ATC about the expected programmed behavior of the UA under LC2L. While predictability needs to be ensured, there were different opinions as to the actual procedure to follow depending on the progress of the flight. For example, while in most situations the preferred behavior may be to enter a holding (or a circling) pattern in a particular location, if the flight were close to the runway, the preferred behavior may be to continue to land. Another challenge is maintaining safety under LC2L when there are hazards that cannot be mitigated by ATC (e.g., diverting other traffic). For example, a UA under LC2L may run into weather systems along the route of its contingency plan, traffic that is not communicating with either ATC or an operator, or other UA also experiencing a LC2L.

4.4.2 Loss of Radio Communication with ATC

In the near-term it is expected that ATC voice communications will be relayed through the UA. Using that architecture, a loss of radio communication with ATC may occur simultaneously with a LC2L or independently.

The procedures for loss of radio communications for UAS should mimic the procedures currently used for crewed operations. However, if lost radio communications occur with a LC2L, LC2L procedures should be followed. If it occurs independently, loss of radio communication procedures, or the No Radio (NORDO) procedures, should be followed. Unlike crewed operations, the remote pilot may have the additional capability to use alternate means to establish communication with ATC (e.g., over a phone line).

4.4.3 Loss of DAA Functionality

If DAA functionality is lost, an emergency declaration may be required to ensure that the UA remains well clear of other aircraft, including non-cooperative VFR traffic not communicating with ATC. A loss of DAA functionality may occur when the C2 link is lost if the link is required to initiate a maneuver (e.g., the DAA system is not autonomous), or if the C2 link is required to transmit surveillance information (e.g., if the DAA system relies on surveillance from ATAR and/or a GBSS).

4.5 Taxi, Takeoff, and Landing

Taxi and other surface operations, in addition to takeoff and landing, are operations which can be unique to a given airport with certain ground-based support infrastructure equipage level. Many challenges in these areas exist. The following paragraphs will discuss, in a general manner, some of the challenges.

4.5.1 Taxi

To achieve efficient operations and mitigate latency due to the C2 link, the UA will need to automatically taxi on the surface. During taxi at a towered airport, the UA needs to be able to follow taxi instructions from the tower controller. At a non-towered airport, the UA needs to be able to determine its own taxi route. At all airports, the UA will need to detect and avoid collisions with other aircraft, ground vehicles, and other obstacles. The UA will also need to provide necessary communications, whether that is communicating with ATC at towered airports, or that is providing intent over CTAF at non-towered airports. The UA will also need to comply with any airport movement area restrictions, such as holding short of active runways. The UA should not block the runway, runway entrance, runway exit, or taxiways. Blocking these places could cause not only a major disruption of the airport traffic management, including a closure of the active runway, but also a safety hazard for other air traffic, and is highly undesirable. Standardizations of the UA taxi operations and performance requirements may need to be established.

4.5.2 Takeoff and Landing

Takeoff and landing are particularly challenging phases of flight. For both phases, there is a need to ensure that the runway is clear of obstacles, including other aircraft. Additionally, given the proximity to the ground during takeoff and landing, any aircraft instability (e.g., stall/spin) leaves to the UA little or no time for recovery. For such time-sensitive vehicle control when a C2 link system delay is present, automatic takeoff or landing capability with an RP overriding function is desirable. Furthermore, aborting a takeoff or landing requires swift decision making and action from the pilot, where C2 link system delays of even a fraction of a second may be unacceptable.

For instance, during a takeoff roll on a runway, the UA accelerates to V_1. V_1 is 1) the maximum speed in takeoff roll at which—if the takeoff is to be aborted—the pilot must take the first action to stop the aircraft within the remaining runway length, and 2) the minimum speed in the takeoff roll—following a critical engine failure for multi-engine aircraft—at which the pilot can safely continue the takeoff given the remaining runway length. If the takeoff needs to be aborted when approaching to V_1 for obstacle avoidance, engine failure, etc., the decision of go/no-go must be made quickly, taking several complex and dynamic factors into consideration, such as the vehicle speed, the remaining runway length, the runway conditions, and the aircraft weight. This decision is challenging even for an onboard pilot. It will likely be even more difficult for the RP to receive telemetry data, identify the problem, make the decision, and send the command to the UA in timely manner when a C2 link system delay is present. Likewise, if a landing needs to be aborted due to a hazard on the runway, wind shear, unstable approach, etc., the land/go-around decision has to be made and the command has to be sent to the UA quickly. Therefore, these processes likely need to be autonomous with an RP overriding function.

Not all runways may be suitable for UA approach and landing. If the UAS requires both vertical and horizontal guidance to follow the glide slope down to near the runway touchdown point, the runway must have at least one precision approach procedure, such as instrument landing system (ILS) or ground-based augmentation system (GBAS) landing system (GLS). Both ILS and GLS have Categories I through III (CAT I/II/III), and CAT III has three subclasses, CAT IIIa, IIIb, and IIIc. Only the CAT IIIc guides the aircraft all the way to the runway surface. ILS III is an expensive system, and typically limited to major commercial or high-traffic airports. At these airports, only some runways may have CAT III. GLS was introduced as a more affordable alternative for ILS, as one system can provide service for all runways at an airport. However, GLS is not a fully-fledged technology (currently only CAT I has been fielded) and still may be economically out of reach for smaller airports. For the UA to be able to operate at smaller airports, the challenges are 1) to enable the UA to land with ILS/GLS CAT I (or II), or even non-precision approach procedures, and 2) to deploy GLS CAT I/II/III to more runways.

4.5.3 Airport Infrastructure

During taxi, takeoff, and landing operations, there is need to detect other traffic or object on the taxiways or the runway. The ATAR used in the airborne DAA currently has limitations in detecting other aircraft or object on the surface or at low altitudes due to ground clutter issues. For the airport to be able to accommodate UA traffic, the ground clutter issues need to be solved by, for instance, better filtering, sensor fusion methods, or a GBSS. Alternatively, a ground crew could serve as a ground observer who communicates potential conflicts to the RP. In order to ensure the safety and predictability of the UA behaviors, some standardizations of these ground-based support systems may need to be established.

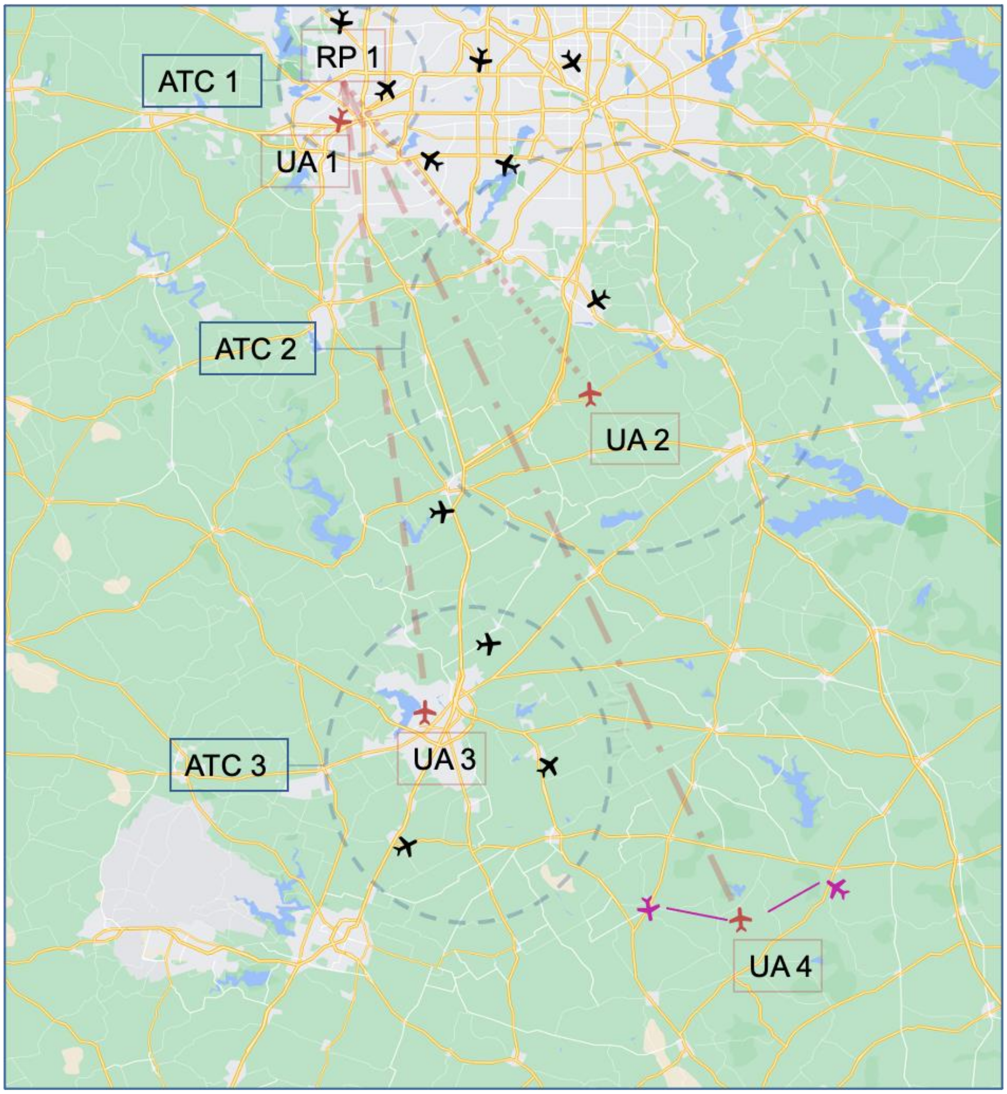
4.6 m:N Operations

Many challenges associated with m:N operations stem from human machine teaming issues, including automation performing pilot tasks, humans shifting to supervisory roles, and the overall human-system integration issues and roles/responsibility allocation. These RP effects may become noticeable to ATC when the m:N operations are conducted in controlled airspace. For example, a busy RP managing multiple UA may not respond to controller instructions within an expected or acceptable timeframe.

Many factors contribute to high RP workload and task complexity when an RP is supervising several UA. Some of these factors are depicted in the examples below where one RP (RP1) is located at Fort Worth Alliance Airport, concurrently supervising four UA: UA1, UA2, UA3, and UA4 (Figure 5). The current day IFR procedures (i.e., without any additional technology or operational procedures and including communication with ATC) are assumed in these examples to illustrate the m:N operations challenges.

1. RP1 needs to be managing at least four C2 link systems (minimum one link per UA) each of which may be using terrestrial or SATCOM link, each with different performance characteristics. Monitoring multiple C2 link systems for N UA is likely not manageable for a single human RP and may require additional technology and/or new operational paradigms.
2. Assuming that three of the UA are currently operating in three different ATC sectors (ATC1, ATC2 and ATC3), then RP1 would be communicating with three different ATCs. In addition, if UA4 is operating in a CTAF environment, then RP1 would also need to be on the CTAF. Assuming voice communications are used, this scenario would result in human factors issues regarding listening to and responding on multiple frequencies simultaneously.
3. Another challenge is the need to aviate, navigate, and/or communicate for multiple UA simultaneously. This challenge is especially acute when traffic near one or more of the UA is non-cooperative, such as a glider operating without a transponder or radio. Conventionally, a pilot onboard would "see and avoid" such traffic as required by 14 CFR §91.113. However, for a UA, there is no pilot onboard, thus the function must divert to onboard technology and automation, such as a DAA system.
4. Each of the four UA could also be in a different phase of flight, each of which introduces a different level of task complexity.

5. Finally, one or more states of LC2L can occur, whereby the RP loses command and control over the UA. It is possible that under these circumstances, the UA experiencing a LC2L may require additional attention that could distract the RP from their other UA.



(Background map data © 2022 Google)

Figure 5. Example m:N Operations

The highest achievable m:N ratio will ultimately be determined by the UAS manufacturer's ability to prove that the proposed m:N operations can meet the NAS performance requirements and maintain safety. Ensuring such a path forward for certification processes for m:N operations may be a challenge.

4.7 Communications Operational Challenges

To enable UA air cargo operations, a standardized C2 and communications architecture that can provide for UA command and control, RP communications with ATC, RP interactions with NAS operations, and any RP communications with third-party service providers needs to be developed. Figure 6 depicts examples of challenges that the communication architecture will need to address. The architecture should initially provide core C2 and communications functionality near-term (the blue arrows in Figure 6), and as future UAS operations are developed, mature to a far-term configuration that provides improved capabilities and performance (the orange arrows in Figure 6).

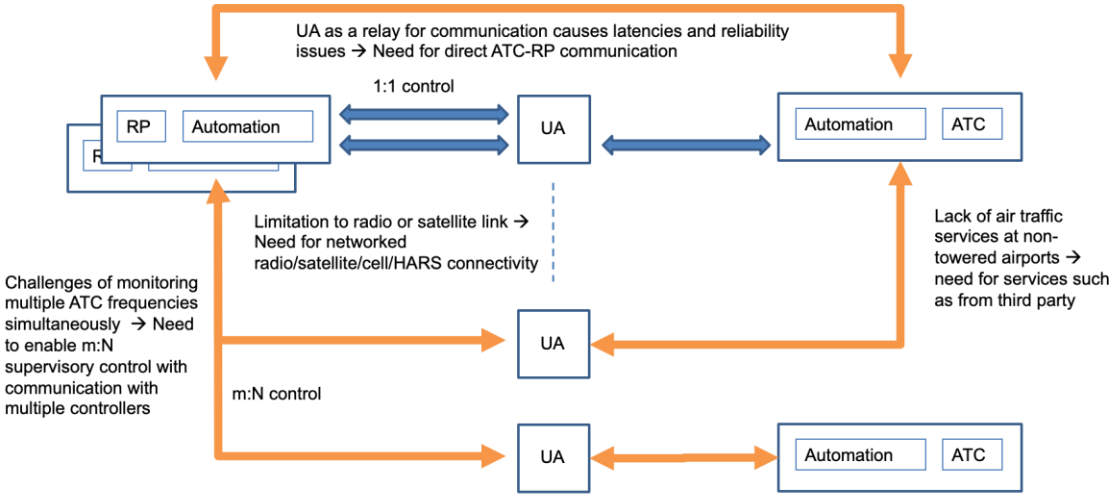


Figure 6. Communications Operational Challenges

Communication challenges identified in Figure 6 include the following:

- There is need for development of and access to radio or satellite link systems capable of initially providing 1:1 RP-UA control with UA as a relay for RP-ATC communication. Only limited standards currently exist from which to develop these systems.
- Large-scale mobile network systems will be needed to provide dynamic connectivity between remote pilots and the UA they control. This includes, for example, development of network capabilities that provide connectivity to multiple C2 link systems (radio, satellite, cellular, HARS).
- Automation or autonomous systems may require additional C2 link specifications or performance characteristics.
- With the focus on regional airports, air traffic services may be lacking at small non-towered airports. Such services may be provided in the future by third-party service providers, which requires seamless data and information distribution from NAS/FAA services and third-party services for operations. Secure and resilient ground networks will be required to provide access to this information.
- Latencies associated with the relay-through-the-UA approach for RP-ATC voice communication create a need for developing reduced communication latency using direct ATC-RP communication. Elimination of the relay-through-the-UA approach using ground network digital voice technology is seen as a potential alternative. (Any change to the voice communication system to use ground based digital networks would need to maintain ATC, pilot, RP airspace situation awareness by emulating party-line operation.)
- m:N operations bring many challenges as mentioned above including the need to control multiple vehicles potentially with different links and to monitor multiple ATC frequencies simultaneously. Therefore, there is need to develop methods to ensure correct connection between multiple RPs and UA, or between multiple UA and an RP, at the correct moment. Network elements within a UA C2 operations network could assist with directing specific RP to UA traffic for these operations.

5 Potential Solutions

In this section, potential solutions to the operational challenges listed in Section 4 are presented. This list of solutions is not exhaustive and will be updated as research is conducted to trade different solutions in terms of their feasibility and benefits. The solutions are not intended to match the challenges one to one; rather, a solution may address multiple challenges and a challenge may be addressed by multiple solutions. Table 4 shows what challenges each proposed solution addresses, where an X symbol is placed in a cell where a solution is believed to address the challenge.

Table 4. Challenge-Solution Mapping

		Operational Challenges						
		4.1 Flight Route Planning	4.2 Separation and Flow Management	4.3 Traffic Pattern Integration	4.4 Contingency Management	4.5 Taxi, Takeoff, and Landing	4.6 m:N Operations	4.7 Communications Operational Challenges
Potential Solutions	5.1 Scalable Communication Architecture	X	X	X	X	X	X	X
	5.2 Data Link		X				X	X
	5.3 Designated UAS Corridor		X				X	
	5.4 Crew Planning for m:N Operations		X				X	X
	5.5 Flight Route Optimization	X	X		X		X	
	5.6 Traffic Load Level Control		X					
	5.7 Trajectory Solutions with Data Link	X	X	X	X		X	
	5.8 Automated Hazard Avoidance for m:N Operations			X		X	X	
	5.9 Traffic Pattern Integration (TPI) Tool			X				
	5.10 Standard LC2L Procedures	X	X		X			
	5.11 Automated Hazard Avoidance under LC2L			X	X	X	X	
	5.12 Auto-Taxi, Auto-Takeoff, and Auto-Land	X		X	X	X	X	
	5.13 GCS User Interface for m:N Operations						X	X

The solutions represent different elements that interrelate with each other forming a full concept. Figure 7 shows one perspective of how the solutions interrelate functionally as the UAS operation is conducted in the airspace. First, underlying all the functional elements, a scalable communication and C2 architecture offers solutions that address the communication challenges in particular but also indirectly helps address all the other challenges as shown in Table 4. It includes key features such as a multi-link management service, direct pilot-ATC Voice Over Internet Protocol (VoIP) communication, message routing for m:N operations, and the use of data link in addition to voice. Then Figure 7 shows the functional solutions starting from the most strategic (top) to the more tactical (bottom) functions.

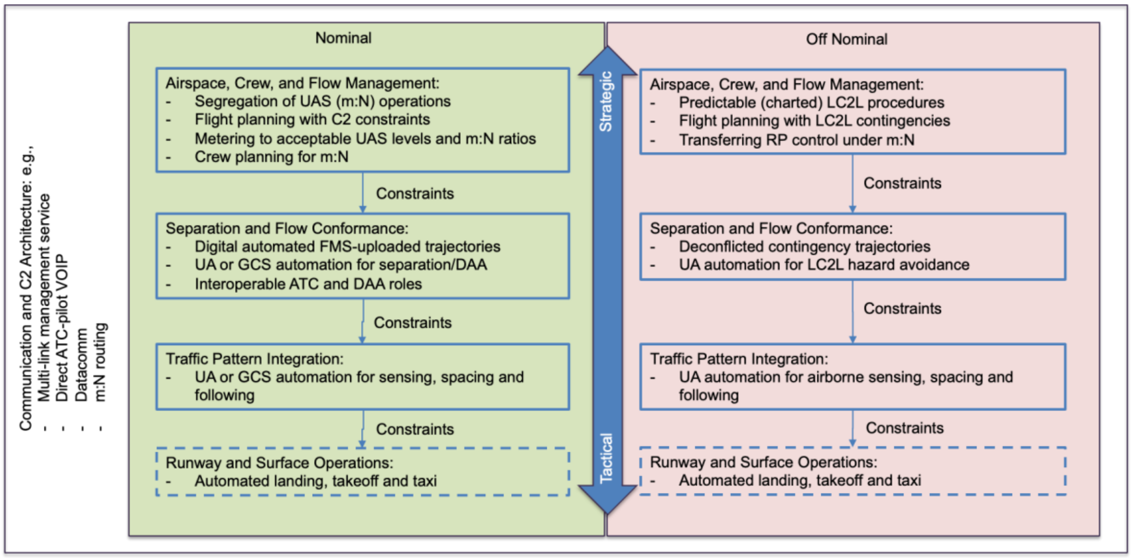


Figure 7. Potential Solutions and Their Interactions

5.1 Scalable Communication Architecture

To enable safe and efficient UA cargo operations, a standardized and scalable C2 and communications architecture for UA command and control, and RP interactions with NAS and UA third-party service providers must be established. For command and control, the architecture will need to securely connect RPs with their aircraft using an infrastructure comprised of intelligent routing within ground-air networks that use resilient radio frequency (RF) link systems to safely operate the UA. C2 will include delivering commands and information from an RP to all systems onboard UA, and for the return of UA system-status telemetry to the RP and to ground services involved in airspace tracking and monitoring. The C2 link system would also, initially, provide the connection for all dialog and data link system messaging between an RP and ATC. Later concepts of the architecture look to improve performance using advanced digital data and voice systems operating over ground networks while still maintaining an FAA preference for legacy airspace situation awareness.

In addition to providing C2 and communications operations, the architecture will need to include communication of data and information between operators, third-party service operators and FAA services. These services would be interconnected within a data-centric system model for distribution and access to accurate near real-time information using high speed data networks, inline with FAA NextGen planning. With the increased operational load that UA would place on the NAS, the ability to process information and rapidly share data will be critical to maintaining safe UA operations. A robust architecture that can inherently deliver accurate, secure, and timely information will enable these unique vehicles' operations, and help to alleviate all challenges defined in Section 4.

Appendix A.2 presents near-term and far-term concepts for C2 and communications architecture to support general UAS operations in the NAS based on the near-term and far-term PAAV concept assumptions (Section 3). This near-term and far-term approach assumes an initial architecture development effort (near-term) to form a core architecture and infrastructure. The near-term operational state introduces new functional elements, baseline capabilities, and secure network interoperability that can be upgraded and modified in the future to form a far-term or end-state configuration. The far-term architecture incorporates advanced PAAV concept elements identified in the far-term assumptions of Section 3.

Scalable communication architecture addresses the following challenges (see Table 4):

- Flight route planning (Section 4.1) by providing an infrastructure that can communicate flight route plan information and coordinate acceptance of, or deviations to, flight plans between UA airline operations centers (AOCs) or NAS dispatch managers and UA RPs.
- Separation and flow management (Section 4.2) and traffic pattern integration (Section 4.3) by providing reliable and resilient RP to UA C2 capability, and an efficient infrastructure to enable dialog between an RP and responsible airspace management authorities.
- Contingency management (Section 4.4) by providing reliable continuous communications (dialog) between an RP and air traffic management to effectively coordinate contingency operations.
- Taxi, takeoff, and landing (Section 4.5) by initially providing reliable surface C2 with visual capabilities for taxi operations and C2 for commanding and monitoring of onboard, automated flight systems for takeoff and landing. Provide scalability to mature and adapt to future levels of automation introduced for these phases of flight.
- m:N operations (Section 4.6) by providing architecture components and functionality that assist with efficient, focused RP to UA, C2 and voice/data traffic for RP handoff operations and eventual operations where multiple UA may be flown by one RP.
- Communications operational challenges (Section 4.7) by providing a scalable (i.e., near-term to far-term) C2 and communications architecture plan that enables safe and resilient UA flight operations and generation and distribution of all data, information and dialog.

5.2 Data Link

Data link offers digital communication capability between ATC and pilots. For example, Controller-Pilot Data Link Communication (CPDLC) is a data link technology in which digital messages are sent between ATC and pilots, where the messages could follow a standard format or be free text. CPDLC could alleviate the issues of UA voice delays, such as increased chance of step-ons, when the ATC radio frequency is congested. It may also help to reduce instances where ATC instructions are misunderstood. If a CPDLC message from the ATC was sent in a loadable format (i.e., a format that can be directly loaded into an FMS for guidance, navigation, and control purposes, but still requires the pilot's command to be executed), it could reduce RP mistakes from manually typing the new instructions into the system. Future m:N operations especially will likely require loadable, CPDLC-like data link messages to prevent a single RP from having to monitor multiple radio frequencies simultaneously, which can hinder an accurate and timely response to ATC instructions.

In order to support m:N operations, CPDLC (or CPDLC-like data link) should be available in all airspaces where these UA will operate, including the TRACON and airport airspaces if m:N operations are to occur in these airspaces. The CPDLC capability may also need to be extended to allow complex messaging (e.g., allowing multiple simultaneous requests from an RP in one message, such as altitude and route changes), immediate and expeditious instructions, approach clearances, and free text in order to enable a single RP to manage all required ATC communications for multiple UA accurately and in timely manner.

Data link addresses the following challenges (Table 4):

- Separation and flow management (Section 4.2) by reducing UA voice delay.
- m:N operations (Section 4.6) by helping the RP to monitor multiple ATC radio frequencies and respond in timely manner.
- Communications operational challenges (Section 4.7) by providing communication means to support m:N operations.

5.3 Designated UAS Corridor

The cooperative corridor concept for UA operations is being considered by the FAA. A corridor is envisioned as a predefined designated airspace through which approved flights can be routed. Access to this designated corridor may be restricted to UA in order to promote the advancement of novel UAS-enabling technologies or, alternatively, may be based on specific equipage and performance characteristics so that the corridors remains accessible to the other flights. Protocols for entering and exiting a cooperative corridor are needed to ensure interoperability with the existing NAS infrastructure. The designated corridors may be similar to the NASA's Extensible Traffic Management (xTM) cooperative control environment concept, as well as the SUAs currently used in the NAS. Corridor air traffic management services would be provided by licensed service providers, not by the FAA. This enterprise approach is similar to the approach taken by the Urban Air Mobility (UAM) concept, which utilizes Provider of Services to UAM (PSU) [18].

One of the benefits of the corridor concept is that FAA ATC is not providing separation or flow management, so reliance on ATC radio voice communications is reduced, alleviating a significant barrier to scaling to m:N operations. Designated UAS corridors may enable the introduction of m:N operations into the NAS, at least until other solutions listed in this section may enable the seamless integration of UA with traffic controlled by ATC.

A drawback to the corridor concept is the lack of flexibility in the route options for the UA. An expansive corridor network is unlikely as the corridor blocks volumes of usable airspace away from other non-participating traffic. If route options are limited, then corridors would be vulnerable to weather and other airspace restrictions that may block the corridor routes. If such a blockage occurs, the UA may need to be grounded until the weather dissipates or the restriction is lifted. In addition, especially for regional cargo operations, the UA may need to fly additional distances to join one of the available corridors from its origin and exit the corridor towards its destination.

Another challenge is that, if any of the airports that the UA uses, including potential contingency airports, is outside the corridor, the UA needs to fly within airspace controlled by ATC, which may require additional UAS equipage, certifications, licenses, and specific procedures, therefore negating some of the stated benefits to the designated corridor operations. The FAA's Advanced Air Mobility (AAM) Beyond Visual Line of Sight (BVLOS) NAS Evaluation (BNE) project is investigating the gaps and impacts of UA operations in the air traffic control environment where ATC provides airspace services to the UA as well as in the corridor control environment.

Other challenges are that the FAA and industry still need to formally define the details of the corridor operations, such as the location, size, and time of operation of individual corridors; rules; regulations; certifications; licensing; contingency procedures; roles and responsibilities between the FAA and the corridor operators; and so forth.

Designated UAS corridors address the following challenges (Table 4):

- Separation and flow management (Section 4.2) by providing designated corridors for the UA traffic.
- m:N operations (Section 4.6) by providing designated corridors for UA traffic that are conducting m:N operations.

5.4 Crew Planning for m:N Operations

A UA can be flown by a sequence of multiple RPs. For instance, the UA can be initially controlled or supervised by an RP-Ground for taxi and takeoff, then handed off to an RP-Terminal for climb to the cruise altitude, then to an RP-En Route who supervises the UA until the arrival phase. For arrival, the UA would be handed off in reverse order. This division of RP phases may be helpful when the UA operates in busy terminal airspaces and/or congested airports, especially in m:N operations. Alternatively, a n RP could be also assigned to a geographical area so that the RP can focus on the specific airspace's procedures and conditions. In that case, the UA would be handed off to another RP every time it crosses a boundary between the geographical areas. Likewise, an RP could be assigned to each ATC radio sector, so that the RP can monitor only one radio frequency instead of multiple frequencies. A downside of assigning an RP per specific geographical area or ATC radio frequency is that it may require a large number of RPs to operate single or multiple UA, and may not be cost effective.

In addition to transferring piloting tasks to different RPs throughout a flight, the remote pilot-to-UA ratio (i.e., m:N) may potentially differ in response to airspace or mission complexity, and may either be constant or dynamically altered as an environment or situation evolves. Discussions with participants in Tabletop 4 (Appendix A.1) revealed that while, for example, a 1:3 or 3:5 m:N ratio may be maintained in a nominal slow-paced en route environment. However, as airspace complexity and time criticality increases, the remote pilot-to-UA ratio may need to be scaled back. Ensuring that an RP is able to maintain sufficient levels of situation awareness, make good decisions and react appropriately, all within a timely manner, will dictate which ratio is best suited for any given environment. The Tabletop 4 participants also suggested that a ratio of 2:5 may be more effective than 1:2, for example, where having each of the remote pilots focus on a coherent subset of tasks may allow higher UA-to-RP ratios.

Beyond simply considering the situation and airspace, the experience levels and the structure of the RPs, including the location and possible collocation of support personnel and fellow pilots, may impact the number of operations a pilot is able to control at once. Multiple RPs may be collocated at a flight operations center (FOC) to facilitate handoffs of UA between RPs, information sharing, and coordination, as well as to provide assistance when RP workload becomes high. Collocating the RPs at the FOC is expected to be more cost effective for business than distributing RPs at many airports. The SMEs from Tabletop 4 listed potential procedural and technological solutions that may increase the capacity of an individual pilot to control multiple aircraft simultaneously (to be included in future versions of this document).

One of the main challenges of m:N operations is that a single RP would need to listen and respond to multiple ATC radio frequencies in timely manner. Data link technologies, such as CPDLC, may alleviate the challenge, though CPDLC alone is probably insufficient (see Section 5.2). Combining CPDLC with other constructs, such as the ability to compute closed-form trajectory solutions that solve multiple airspace and traffic problems simultaneously with a single FMS-loadable CPDLC message, may help enable m:N operations (See section 5.7). Adapting digital flight rules (DFR) in place of VFR or IFR to allow air traffic to self-separate from each other may be another option to enable scalable m:N operations in the far term. If ATC voice communication is to stay, natural language processing and speech synthesis technologies may be utilized to support the RP conducting m:N operations in future.

If a LC2L situation occurs with one of the UA supervised by an RP, the workload of the RP is likely to increase significantly leading to an overload situation and potentially compromising safety. The SMEs at the tabletop activity recommended that in this situation, the RP should continue to monitor the UA under LC2L, while handing the other UA to other RPs.

It is assumed that there is only one RPIC per each UA at any given moment during the flight, though the RPIC role may be transferred or assigned to another individual during the flight. The RPIC for the departure phase would make the go/no-go decision for the flight even if the RPIC responsibility will be handed off to another RPIC later in the flight. (In case of Part 121 operations, it is expected that the RPIC for the departure phase would sign the flight release form for the flight with the dispatcher.)

Crew planning for m:N addresses the following challenges (Table 4):

- Separation and flow management (Section 4.2) by planning for the appropriate m:N ratio for each UA flight segment.
- m:N operations (Section 4.6) by planning for the appropriate m:N ratio for each UA flight segment.
- Communications operational challenges (Section 4.7) by planning for the appropriate m:N ratio for each UA flight segment considering the C2 link signal availabilities.

5.5 Flight Route Optimization

UA flight route optimization for safety (e.g., hazard avoidance) and efficiency (e.g., fuel and flight time reductions) may require taking several unique elements into account, such as C2 link system coverage, airport, ATC traffic load, and weather. Not only each individual element's direct effects need to be considered, but also interactions among them. For example, the availabilities of the options for weather avoidance routes may be simultaneously restricted by C2 link signal availabilities along each route at the time when the UA flies through the area. The nominal route as well as all the potential contingency routes need to be evaluated against these elements. The route must be closed all the way to the runway. It is conceivable that the RP rejects a route amendment if the new route would not work for the UA or there is no safe contingency route available. The complex route optimization may be performed with special decision-support tool software or third-party service providers. Some key information may be available through public information (e.g., the FAA's System Wide Information Management, or SWIM), or may be obtained through third-party service providers (e.g., weather forecast, C2 link coverage).

Flight route optimization is primarily conducted predeparture. However, even after a flight departs, the flight route optimization may need to be continually reevaluated in response to changes in C2 coverage or other elements listed below. If the UA receives a route amendment in mid-flight, the contingency routes may also need to be updated and uplinked to the UA simultaneously, or as soon as possible, as a LC2L could happen at any moment. The ATC must be also informed of the updated contingency routes and, in response to a LC2L, if an updated contingency route was selected. An alternative would be that LC2L contingency plans are continually calculated by the UAS, but communicated only when one of the plans is required to be executed. This option would allow the UAS flexibility to have multiple contingency plans without burdening the ATC, but also rely on timely communication establishment between the RP and the ATC when a LC2L occurred.

The following subsections describe some of the elements to be considered:

5.5.1 C2 link system coverage

Terrestrial and SATCOM link coverage along the route, including the signal reliability, transmission latency, and any outage, need to be considered. Real-time health monitoring of the C2 link, such as maps of satellite signal outages and availability may be utilized. Similar maps currently exist (e.g., Wide Area Augmentation System display, [19]) and can be tailored for C2 link availability evaluation purposes. Some C2 link systems may have a maximum number of UA that can be supported at any one time. The C2 link signal reliability may be affected by aircraft antenna orientation while maneuvering, the transmitter and receiver characteristics, terrain interference, and atmospheric conditions. Modeling these effects may be beneficial for the flight route optimization.

5.5.2 Airport

To support UAS operations, an airport needs to be appropriately equipped, including the contingency airports, although the contingency airports may have reduced requirements due to lower likelihood of use. For example, the ramp area may need to offer the necessary cargo-base infrastructure and ground crew to support the UA pre- and post-flight activities. UA taxi operations may require precise measurements of taxiway and runway topology as well as awareness of certain ground-based surveillance and taxi guidance systems. To support UA takeoff, landing, and traffic pattern integration operations, an airport may need to have GBSS and precision approach procedures (e.g., ILS or GLS). The GBSS coverage areas may also need to be considered if there is any surveillance blockage due to ground obstacles. If minimizing the C2 link delay is desired, a GRS for terrestrial link may need to be present at or near the airport to allow radio-line-of-sight communication.

5.5.3 ATC traffic load

It may be advantageous for the UA operator to intentionally select airspaces that are predicted to have relatively low traffic loads to increase the safety margin of UA operations. A human-in-the-loop (HITL) simulation study [16] demonstrated that lower ATC traffic load level in an en route sector reduced the negative impacts of long UA voice delay on the ATCs' subjective workload ratings. In addition, if the ATC workload is not too high, the ATC more likely has extra time to assist the UA on the LC2L procedure.

5.5.4 Weather

Like crewed aircraft flights, the UA flight must avoid hazardous weather. However, additional considerations must be given to the UA route to ensure the weather avoidance route has sufficient C2 link system coverage and potential alternate airports that can accommodate the UA. Considerations also need to be given to any potential contingency routes as well as missed approach procedures at the destination airport, as currently the UA is unable to accept a visual approach clearance. Not only current weather data but also weather forecast information must be used to evaluate expected weather conditions along a UA's route. VMC, where a large number of VFR flights may be expected in the region, could be a unique hazard for the UA.

Flight route optimization addresses the following challenges (Table 4):

- Flight route planning (Section 4.1) by computing the optimal flight route.
- Separation and flow management (Section 4.2) by computing the optimal flight route that avoids high density airspace and weather hazards.
- Contingency management (Section 4.4) by computing the contingency route that avoids high density airspace and weather hazards, and leads to an airport that can accommodate UA.
- m:N operations (Section 4.6) by computing the optimal flight route for each UA that avoids high density airspace and weather hazards.

5.6 Traffic Load Level Control

Section 5.5 described flight route optimization with respect to ATC traffic load. That was an optimization from the UA operator's viewpoint. Likewise, there may be benefits on the ATC's side in implementing the following load control strategies in order to mitigate the risks of having the UA flights in the en route airspace:

1. Restricting background traffic volume levels in areas where UA operate
2. Applying larger separation standards for UA than those for crewed aircraft
3. Limiting the total number of UA allowed to concurrently fly in each sector

Mitigation 1 can be implemented via departure metering, which may be done without raising the en route sector ATC's workload and thus may be a preferred approach. Mitigation 2 may require changes in the current ATC procedures and En Route Automation Modernization (ERAM) algorithms, and thus may be less preferred. Mitigation 3 can be accomplished by ATC rejecting the UA from entering the sector airspace. This approach could be disruptive for both the UA and the ATC sides, as the UA may need to enter an airborne holding (or circling) pattern near the sector boundary. To support these mitigations, metrics are needed to assess the impact of the UA on the complexity of the airspace and workload of ATC and pilots, such that appropriate limits are set for the level of traffic, UA ratios to other traffic, and separation criteria.

Traffic load level control addresses the following challenge (Table 4):

- Separation and flow management (Section 4.2) by providing means for the ATC to reduce the risks of having UA in the airspace.

5.7 Trajectory Solutions with Data Link

As described in section 5.2, data link is a core concept element for enabling m:N by reducing the need for pilots to monitor multiple radio frequencies simultaneously for voice-based traffic instructions. Data link communications alone, however, are likely insufficient to address the entire m:N problem. To further minimize workload, trajectory-based solutions that solve traffic problems in a comprehensive manner—thus significantly reducing the number of required maneuver instructions—can be delivered via data link and loaded into a UA FMS for automatic flight guidance and control.

The concept of tailored trajectory solutions for UA is illustrated in Figure 8. In this concept, comprehensive trajectory solutions are computed for UA that satisfy a multitude of constraints simultaneously. These constraints include remaining safely separated from other traffic, complying with airspace and airport capacity limitations, and avoiding regions of hazardous weather and restricted airspace. Constraints on trajectory solutions can be augmented to include those particular to UA operations, such as expanded separation criteria (if deemed necessary) and avoiding regions of poor C2 link availability, which result from the airspace and flow management solutions mentioned above. Importantly, trajectory solutions account for winds, ensure 'flyability' given individual aircraft performance capabilities, and maximize fuel efficiency under the constraints specified. The solutions are trajectory-based in that their computation process involves four-dimensional (x, y, z, and t) trajectory calculations to detect and resolve problems. The outputs from the process, however, are discrete parameters that define a future flight profile that satisfies constraints, including revised fight routing in the form of waypoints, altitude profile, speed profile, and crossing conditions at specified fixes. In this manner, solutions consist of instructions similar to those issued by ATC today but with the advantage of combining route, speed, and altitude commands into a single, comprehensive digital flight instruction.

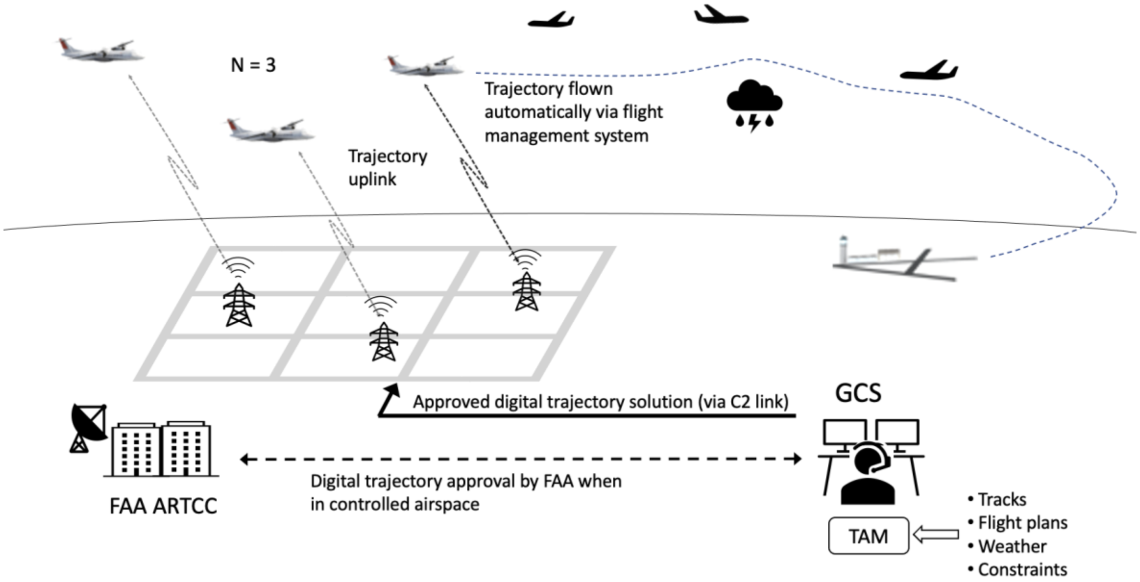


Figure 8. Trajectory Solutions via Data Link – OV-1

Trajectory-based solutions are *closed form* in that they ultimately return the UA to its nominal flight plan whenever possible. The look-ahead time horizon for resolving problems is configurable based on the type of problem being resolved and the uncertainties therein. The predictive accuracy of the automation will allow for resolution time horizons up to and beyond those associated with current ATC actions. Conflict resolution will generally protect against separation between aircraft pairs that falls below radar separation minima, which for conventional operations today are typically 5 nmi horizontal and 1,000 ft vertical in en route airspace and 3 nmi and 1,000 ft in TRACON airspace. While look-ahead time horizons and protective volumes are well outside those specified for DAA (as described earlier), interoperability between trajectory solutions and DAA deserves further study, especially given that trajectory solutions will update whenever a new conflict or other airspace problem appears.

While the capability described here can use published procedures such as SIDs and STARs specified in a flight plan to establish 'backbone' flight intent near airports, it can also support—and digitally convey—*dynamic procedures* tailored for fuel efficiency, noise mitigation, weather avoidance, and traffic flows. While this capability can provide comprehensive (end-to-end-complete) intent sufficient to deliver UA to the runway via a direct precision approach in a conflict-free manner, it can also potentially help insert UA into a traffic pattern.

NASA's Tailored Arrival Manager (TAM) [20] provides a starting point for the capability described here. TAM relies on NASA's AutoResolver algorithm [21] for solution generation. TAM development began in 2019 to support a proof-of-concept flight test of trajectory solutions via data link. TAM solutions were automatically converted to digital CPDLC messages and rapidly uplinked to an aircraft using the FAA's operational data link capability. Once received on the flight deck, a given CPDLC message was loaded via a single button press by the pilot into the aircraft's FMS and shown on the aircraft's navigational display as a provisional trajectory pending pilot approval. If the pilot approved the solution, they would simply press a WILCO button. In an operation where the solution was sent by ATC as an instruction, pressing the WILCO button would downlink a CPDLC message acknowledging the pilot's intent to comply with the ATC instruction. For UA applications, CPDLC-like messages could be similarly loaded into an FMS located at a remote pilot's GCS for conversion into command instructions sent via the C2 link. CPDLC is mentioned here for describing the notion of relying on structured data link messages that integrate directly with UA FMS automation to minimize workload and prevent errors associated with manual entry of trajectory solution elements.

The concept elements described here can also help manage UA operations under LC2L situations by providing comprehensive and continuous flight intent that stretches from the UA's current position to its destination. Trajectory solutions effectively amend the nominal IFR flight plan and can establish the last-known intent of the UA for situational awareness and predictability among ATCs and other flight operators [22]. Trajectory solutions to alternate airports or landing zones for LC2L contingencies can be computed and exchanged using the general concept described here. LC2L solutions can be updated as the UA progresses to help minimize traffic disruptions under LC2L events, including de-conflicting from traffic, weather, and the LC2L trajectories of other UA.

In Figure 8, the TAM solution generator and user interface is shown allocated to the RP's GCS. For operations within controlled airspace, electronic approval of the digital solution trajectory is requested by the FAA (dashed line at the bottom of the diagram) prior to sending it to a UA via data link from the GCS. Alternatively, TAM functionality can be allocated directly to the FAA Air Route Traffic Control Centers (ARTCC) relevant to the UA mission. In either configuration, there are no changes implied to separation assurance responsibilities, which continue to reside with the FAA. FAA approval of TAM solutions and subsequent updates to IFR flight plans could be managed without a full integration on a Radar-Side display; for example, these functions could be managed by an ARTCC Data-Side (D-Side) controller at a sector position, an ARTCC traffic management coordinator, or possibly by another ARTCC position dedicated to UA flight plan approval and FAA system updates. The general capability described here could also work well in a tailored flight rule environment (beyond IFR) where the operator or third-party service provider is granted the responsibility of separating UA from other traffic.

Trajectory solutions with data link addresses the following challenges (Table 4):

- Flight route planning (Section 4.1) by computing and uploading a deconflicted route for the UA that is updated, if needed, as the flight progresses.
- Separation and flow management (Section 4.2) by computing and uploading a deconflicted route for the UA that is updated, if needed, as the flight progresses.
- Contingency management (Section 4.4) by computing and uploading a deconflicted contingency route for the UA that is updated, if needed, as the flight progresses.
- m:N operations (Section 4.6) by a) reducing multiple control instructions into a single trajectory-based message that resolves multiple traffic problems simultaneously and b) communicating FMS-loadable messages by data link to reduce pilot workload associated with voice-based communications and manual UA command entries.

5.8 Automated Hazard Avoidance for m:N Operations

According to the insights from the tabletop participants (Appendix A.1), enabling m:N operations requires significant automation to reduce the pilot workload and improve response time in time-critical situations. A digital trajectory, which meets all constraints and is agreed upon by the RP and ATC, may be uplinked to the UA, and then uploaded in the FMS automatically with minimal involvement from the RP (as described in Section 5.7). Such capability can go a long way in automating RP tasks and reducing ATC voice communications. As time-criticality of a hazard situation increases, e.g., in conflict with other traffic, particularly when the RP is supervising many UA, the negotiation between the RP and ATC, as well as obtaining ATC approval for the trajectory, may not be completed in a timely manner to safely resolve the conflict. In such situations, reducing or eliminating the need for ATC involvement for resolving the conflicts by delegating the responsibility to the RP with the adequate levels of automation support from the GCS and UA may be beneficial. Such a concept for delegating separation responsibility to the RPs may be achieved inside designated UAS corridors as described in Section 5.3. In controlled airspace, it requires new regulations such as the DFR which are under research and aim to provide IFR flights, such as the UA, a level of flexibility that is similar to VFR traffic [14].

The UA's ability to automatically initiate a DAA RA maneuver without the RP's command can provide an additional safety net, where the RP's response to a DAA RA was too late or incorrect, which could happen when the RP is supervising many UAs. The RTCA's DO-365B [8] states that automated RA and return to course (RTC) functionality in the en route environment is optional for the UAS equipped with either Class 2 or 3 DAA, which has integrated collision avoidance systems. Appendix R of DO-365B describes the recommended requirements for automated RA and RTC functions. An automated RTC is used after completed execution of an automated RA function. The functionalities will require higher hardware reliability and software design assurance levels for the UAS. Once the C2 link system signals are regained, the system must allow the RP to override the automated RA and RTC functions. The RP may also choose to use the RTC plan included in the LC2L procedures, if that exists. As DAA becomes more automated to enable m:N operations, more research is needed to ensure that it interoperates seamlessly with ATC separation, with clear lines of responsibility and assurance of safety.

Automated hazard avoidance for m:N operations addresses the following challenges (Table 4):

- Traffic pattern integration (Section 4.3) by allowing the UA conducting m:N operations to automatically avoid hazards when the RP input was too slow or incorrect.
- Taxi, takeoff, and landing (Section 4.5) by allowing the UA conducting m:N operations to automatically avoid hazards when the RP input was too slow or incorrect.
- m:N operations (Section 4.6) by allowing the UA conducting m:N operations to automatically avoid hazards when the RP input was too slow or incorrect.

5.9 Traffic Pattern Integration (TPI) Tool

To enable a UAS to accept visual-approach-like clearances, many technical and regulatory advancements are needed. As stated in Section 4.3, in order to fly a visual approach clearance, the aircraft must maintain visual separation from other aircraft, stay clear of clouds, and keep the preceding aircraft and/or airport in sight. Certain technologies or alternative means of compliance may need to be developed to enable visual-approach-like clearances. On the regulatory side, much of the regulatory language will need to be updated to account for the lack of visual capabilities onboard the UA, requiring analysis and flight demonstrations to prove adequate levels of safety are maintained. Further, as the UAS situation awareness is minimally impacted by current meteorological conditions, the current regulations will need to be modified to enable these operations regardless of whether it is VMC or IMC.

To address the limitations of a UAS to accept a visual-approach-like clearance, a TPI tool (an automated decision-support tool) is envisioned to provide an efficient flight path utilizing standardized traffic patterns while providing alerting and guidance to maintain spacing with other aircraft. The tool should determine the appropriate method for joining the traffic pattern based on the local airport conditions, sequencing with proximate traffic aircraft near the airport, and route efficiency. To provide timely alerts and guidance, the tool needs to have accurate prediction of the other traffic's intent to properly predict when a loss of spacing may occur and provide effective maneuver options. Such a prediction of traffic intent is a challenging research area due to the lack of sufficient cooperation and information sharing from VFR traffic that generally use the airport traffic pattern. Further, to maintain interoperability with other aircraft, it is important for the UA to behave in a predictable manner by joining the traffic pattern using approach paths and limiting maneuvers in the traffic pattern.

Due to the heterogeneous mix of aircraft and operations within an airport environment, it cannot be expected that all operators will utilize a common, coordinated system to maintain spacing in the airport traffic pattern. Therefore, each UAS equipped with a TPI automated decision support tool should work independently, and thus, without reliance on direct explicit coordination. Implicit coordination necessary to maintain efficiency and safety may be achieved by the standardization of UA behaviors and spacing objective.

It is also imperative that a TPI automated decision support tool interoperates well with other critical components of the UAS including DAA and other automation tools. While TPI and DAA systems are similar, and both are likely needed to optimize UAS operations, DAA more focuses on maintaining safety, whereas a TPI tool may focus more on operational efficiency.

TPI tool addresses the following challenge (Table 4):

- Traffic pattern integration (Section 4.3) by allowing the UA to enter the traffic pattern.

5.10 Standard LC2L Procedures

LC2L contingency management requires an established, predictable set of actions by the RP, the UA and ATC to permit scalable operations. The basic premise of LC2L contingency management is the presumption of a UA's capability, via its onboard FMS, to follow a preplanned path known to the UA, the RP and ATC while the UA is in a lost link state, referred to as the LC2L procedure. The LC2L procedure describes a set of actions that the UA will follow during LC2L events. Since LC2L can occur during any phase of a flight operation, including while still on the ground, the LC2L procedure could be as simple as stopping in place during pre- or post-flight taxi operations. However, after takeoff the LC2L procedure must define the remaining route of flight, altitude(s), arrival and approach to a landing runway for the mission.

A framework for a basic LC2L procedure that maintains operational safety is based on the concept found in the FAA internal report, “UAS NAS Integration: Lost Link Procedures Concept Document” prepared for the FAA New Entrants Division (ANG-C2) by Cavan Solutions in June 2020, and modified to reflect current progress by ongoing research-driven efforts such as PAAV, as well as related industry activities.

The fundamental concept to address lost link has the following major principles:

1. The UA must initially continue on its current course for an established minimum period of time or until the end of the current ATC clearance is reached. Delaying the UA's possible deviation from its current course enables ATC to determine and enact any necessary course of action.
2. An unambiguous LC2L procedure flown by the UA representing the remaining route of flight for the mission must be commonly understood by the RP and ATC.

A potential method for determining the start of the lost link event and the subsequent actions by the UA, RP and ATC is notionally depicted in Figure 9, with terminology definitions and explanations provided after the figure.

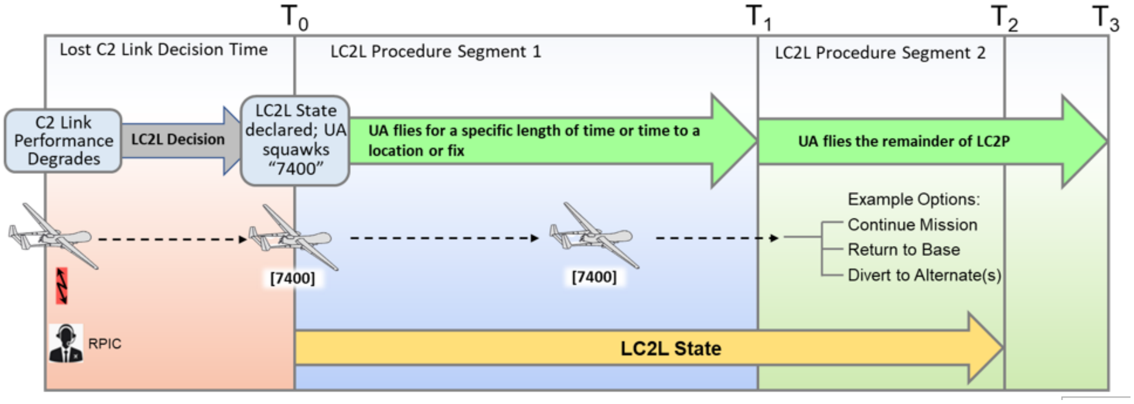


Figure 9. Notional LC2L Event

The protocol illustrated in Figure 9 establishes a practicable set of actions for the LC2L event that are constrained by pre-established timeframes. These time-related parameters are not yet defined, but it is likely that the value of each may differ between operational environments (e.g., en route, terminal) and phase of flight (e.g., taxi, departure, cruise, approach).

- **T_0** : The time at which a LC2L state is declared by the UA automatically squawking 7400, and the UA begins flying Segment 1 of the LC2L procedure. Segment 1 of the LC2L procedure is congruent with the nominal routes.
- **T_1** : The time at which the UA begins flying Segment 2 of the LC2L procedure, which may or may not differ from the nominal route. **T_1** is defined to provide ample time for ATC to become aware of the UA being in a LC2L state, to understand the LC2L route, and to plan for maintaining traffic separation prior to any UA maneuvers. The value of **T_1** may vary with phase of flight and operational environment.
- **T_2** : The time at which the C2 link has been re-established.
- **T_3** : The time at which the LC2L event is over. During the period from **T_2** to **T_3**, ATC and RP coordinate next actions, the UA squawks a code assigned by ATC, and the UA has been commanded to fly a route in accordance with ATC instructions. If C2 link is never reestablished, both **T_2** and **T_3** will be undefined.

One means to ensure predictable behavior and reduce the durations of LC2L procedure in Segments 1 and 2 in the terminal environment is for UA LC2L procedures to be included in published procedures such as IAPs, STARs, and SIDs. There is still a need to communicate *ad hoc* LC2L procedures that are not covered by established standard LC2L procedures. In this case, it is imperative to establish efficient methods for communicating the LC2L procedure to ATC. Domestic military UA operations often rely on establishing telephone communications between the RP and ATC in such instances, but this method is deemed impractical for non-military UAS operations. Integration of UA contingency rerouting with ERAM and/or En Route Decision Support Tool (EDST) is needed. Potential candidate solutions may already exist—e.g., Airborne Reroute (ABRR) is a capability within the FAA's Traffic Flow Management System (TFMS) that is used for tactical reroutes for airborne aircraft. The ARTCC traffic management coordinator uses TFMS route amendment dialog (RAD) to define a set of aircraft-specific reroutes that address a certain traffic flow problem and then electronically transmits them to ERAM for execution by the appropriate sector controllers.

There are several important considerations for the development of the LC2L procedures. The time of exposure to non-cooperative aircraft may be mitigated by landing as soon as possible or climbing to Class A airspace, where (almost) all aircraft are IFR and ATC can ensure separation. If the runway in use changes at the destination airport while a UA is in a LC2L state, the UA may land on the incorrect runway.

Standard LC2L procedures address the following challenges (Table 4):

- Flight route planning (Section 4.1) by providing the standard LC2L procedures for the planned flight route.
- Separation and flow management (Section 4.2) by providing the standard LC2L procedures shared with the ATC to ensure the UA separation from the other NAS traffic.
- Contingency management (Section 4.4) by providing the standard LC2L procedures.

5.11 Automated Hazard Avoidance under LC2L

To maintain required levels of safety and/or efficiency in the NAS, it will be necessary to augment the basic automatic LC2L procedure execution with more dynamic adaptations to situations that cannot be preplanned. The following are the situations that the UA may encounter during LC2L, shown with an example potential solution for each situation in parentheses:

- Traffic conflicts that would result in loss of well-clear (automatic DAA RA maneuvering, see Section 5.8)
- Encountering hazardous weather on the LC2L procedure route of flight (auto hazardous weather avoidance, see Section 5.7)
- Changes in landing configurations at the destination airport, e.g., a runway change from the one specified in the LC2L procedure due to wind shift (auto landing configurations identification)
- Executing visual approach-like clearances to the destination airport (traffic pattern integration, see Section 5.9)
- Detection of runway occupancy at the destination airport (auto go-around)
- In-flight emergencies such as engine failure or critical fuel (auto emergency declaration)

Automated hazard avoidance under LC2L addresses the following challenges (Table 4):

- Traffic pattern integration (Section 4.3) by allowing the UA under LC2L to automatically avoid hazards.
- Contingency management (Section 4.4) by allowing the UA under LC2L to automatically avoid hazards.
- Taxi, takeoff, and landing (Section 4.5) by allowing the UA under LC2L to automatically avoid hazards.
- m:N operations (Section 4.6) by allowing the UA under LC2L conducting m:N operations to automatically avoid hazards.

5.12 Auto-Taxi, Auto-Takeoff, and Auto-Land

Auto-taxiing is a concept whereby the UA can automatically travel from the gate or hardstand to the runway, and the reverse. Auto-taxiing can refer to either automated taxiing or fully autonomous taxiing. While limited automated taxiing, where a UA follows a predefined path, exists in a limited capacity, fully autonomous taxiing, where a UA can taxi to the runway, following ATC commands (e.g., yield to or follow traffic) and integrating with other traffic, does not currently exist. A method to integrate UA with other airport surface traffic was proposed by the German Aerospace Center (DLR) and is called Segmented Standard Taxi Routes [23, 24]. This method defines a published standard taxi route for UA from the gate or hardstand to the active runway as opposed to a taxi route established via ATC-pilot communication. Along this published standard route are mandatory stop points, which segment the standard route. The g round controller would clear the UA to the next point along the route instead of clearing the UA along the entire taxi route. In the event that clearance to proceed past a mandatory stop point is not given, the UA will stop and hold at the stop point. While no comprehensive solution exists at present, it is nonetheless assumed that some form of auto-taxi capability will be necessary to enable integration of UA into the NAS.

Auto-takeoff is currently not used in commercial aviation, but Airbus has successfully tested fully automated vision-based taxi and takeoff in 2020 with a safety pilot onboard [25].

Auto-land technologies already exist to some degree. Auto-land functions have been used during Instrument Landing System (ILS) Category III (CAT-III) approach and landings with onboard pilots' supervision for many years. For PAAV operations, it is desired for the UA to be able to land at an airport without ILS as well, such as an airport with GPS-based or GBSS-based approach procedures. The Garmin Autoland system is an emergency-only system, and automatically activates when the onboard pilot is incapacitated. For such an event, this system automatically declares an emergency, finds an airport, and lands the aircraft. For Garmin Autoland to be able to perform an approach, the airport has to have a GPS-based approach procedure with both vertical and lateral guidance. Use of Garmin Autoland in non-emergency situations is currently prohibited.

Auto-taxi, auto-takeoff, and auto-land address the following challenges (Table 4):

- Flight route planning (Section 4.1) by providing the information about the airports that are equipped for auto-taxi, auto-takeoff, and auto-land by UA.
- Traffic pattern integration (Section 4.3) by allowing the UA to perform auto-taxi, auto-takeoff, and auto-land.
- Contingency management (Section 4.4) by allowing the UA to perform auto-taxi, auto-takeoff, and auto-land.
- Taxi, takeoff, and landing (Section 4.5) by allowing the UA to perform auto-taxi, auto-takeoff, and auto-land.
- m:N operations (Section 4.6) by allowing the UA conducting m:N operations to perform auto-taxi, auto-takeoff, and auto-land.

5.13 GCS User Interface for m:N Operations

A UAS that enables m:N operations will likely be composed of many highly automatic systems, and the RP will be like a system supervisor. The RP will need to be monitoring multiple UA, maintain the situation awareness of each UA simultaneously, and promptly intervene to each UA when needed. There are a number of potential human factors challenges in m:N operations, such as information overload, needs to simultaneously intervene with multiple UA flights, and need to make complex decisions and actions accurately under time pressure, to name a few. If the ATC voice communication stays, the RP needs to concurrently listen to multiple ATC radio frequencies and speak to when needed in timely manner, which may be impossible sometime. Data link, like CPDLC, would help the RP's multi-tasking, but data link alone will be insufficient. The RP also needs to monitor the states of various automated systems and be aware of their modes, programmed behaviors, and limitations. The GCS-UA connections may change dynamically during the UA operations for variety of reasons (e.g., handoff of single UA between two PRs, adding/removing UA per a GCS during m:N operations, two RPs swapping their UA in mid-air, etc.). Which UA the GCS is connected to, or disconnected from, at any moment should be always transparent to the RP. Innovative GCS user interface design solutions to overcome these new challenges for m:N operations will be required.

Identifying required minimum performance of the RP to safely conduct m:N operations, in terms of, for instance, the RP response speeds and error rates, may help when defining GCS user interface requirements and design standardizations, as well as the determination of the feasible m:N ratio. The RP's skill and experience are important elements, and thus training and certification requirements may need to be considered together with the GCS user interface design.

GCS user interface for m:N operations addresses the following challenges (Table 4):

- m:N operations (Section 4.6) by providing the GCS that can be used to conduct m:N operations.
- Communications operational challenges (Section 4.7) by enabling the RPs conducting m:N operations to communicate with the ATC and other parties in timely manner.

6 Summary

In this document, the foundational elements needed to begin defining a concept for PAAV have been identified. These elements include a description of operational context, challenges, and potential solutions. The document explores potential solutions for operations where one remote pilot is managing one flight at a time (1:1) in the near-term to operations where a single pilot is managing multiple flights at a time (m:N) in the further term, in keeping with industry's desire to maximize air-cargo productivity with limited pilot resources. Several potential architectural, operational, and technological solutions needed to achieve these goals were briefly discussed, some of which have been already investigated by the PAAV project team (see Appendix A for the past and current PAAV project work). This document also aimed to identify candidate research areas for the PAAV team to focus on in the future. Overall, it is expected that a significant amount of automation and autonomy technologies will be required to mitigate the challenges and to eventually realize m:N operations. Complex technologies will pose challenges not only in their development but also in testing and certification. Thus, tradeoffs among various levels of automation must be taken into consideration when formulating the PAAV concept. Future revisions of this document will shape the foundational elements described here into a single, cohesive concept description that will further guide PAAV research and development and reflect key findings from analytical studies, simulations, and flight testing.

Appendix A: Projects

A.1 Tabletop Exercises

The four tabletop exercises (or "tabletops") were conducted between August 2020 and May 2022 (Table A.1) and provided a forum for discussions to gather SME insight into future UA cargo operations, with regard to both near-term and far-term implementations. There were a total of 23 days of guided discussion with recently retired ATCs, active military RPs, commercial and airline transport pilots with regional and major airline flight experiences, and dispatchers. Researchers developed and defined specific sets of starting assumptions for each of the tabletops, defining the scope that was to be kept in mind for the discussions. Tabletops 1 through 3 began by investigating more near-term ideas for implementation [26]. Tabletop 4 focused on exploring a more far-term vision, emphasizing a shift from a single operator piloting a single UA for the entirety of its flight (1:1) towards a configuration where a single operator may pilot multiple flights simultaneously (1:N), or where multiple operators may share piloting duties for multiple flights (m:N), potentially for only portions of the UA’s flights. The hazards, issues, mitigations and gaps identified through these activities have helped to identify candidate areas for future research by highlighting the possible barriers to integrating these operations.

The fourth, and the most recent, tabletop was conducted in three sessions over eight days with a total of 13 participants. The first session was four days long and included six pilots and one dispatcher, the second session was three days and included six air traffic controllers, and finally, the last session was a single day with all 13 participants.

Table A.1. PAAV Tabletops

	Tabletop 1	Tabletop 2	Tabletop 3	Tabletop 4
Number of Days	5	5	5	8
Dates	8/24/2020 – 8/28/2020	4/26/2021 – 4/30/2021	6/14/2021 – 6/18/2021	5/16/2022 – 5/27/2022
Number of Participants	9	10	10	13
Participant Occupation	• En Route ATC (2) • TRACON ATC (3) • Airport Traffic Control Tower (ATCT) Controller (1) • Remote Pilot (2) • Pilot - Major (1)	• En Route ATC (1) • TRACON ATC (2) • ATCT Controller (2) • Remote Pilot (2) • Pilot - Major (1) • Pilot - Regional (1) • Dispatcher (1)	• En Route ATC (1) • TRACON ATC (2) • ATCT Controller (2) • Remote Pilot (2) • Pilot - Major (1) • Pilot - Regional (1) • Dispatcher (1)	• En Route ATC (2) • TRACON ATC (2) • ATCT Controller (2) • Remote Pilot (3) • Pilot - Major (2) • Pilot - Regional (1) • Dispatcher (1)
Method	Bowtie Analysis	Bowtie Analysis	Bowtie Analysis	FLEX Method
Topic Areas	• Data Link and Radio Latencies • Radio Failures • LC2L • IFR (UA) and VRF Flight Interactions • DAA • ACAS Xu • Airport-Specific Hazards (at Controlled and Uncontrolled Airports)	• Controlled Arrival & Departure • LC2L Controlled Arrival & Departure • CTAF Arrival & Departure • LC2L CTAF Arrival & Departure • Visual Approach • Metering • Runway Operations • Sequencing • Weather Avoidance	• Ramp Operations • Controlled Surface Operations • CTAF Surface Operations • Controlled Runway Operations • LC2L CTAF Runway Operations • DAA • ACAS Xu • Icing • Off-Nominal Events	• Weather Avoidance • Weather Avoidance – LC2L • DAA Alerting and Guidance • Mid-Flight Pilot Handoff • GCS Position Relief • Multiple ATC Frequencies • Data Link Management • Traffic Management Initiatives (TMI) – Metering • LC2L Descent to Landing • TMI – Holding • TMI – LC2L while Holding • Sequencing • TRACON Resequencing • Missed Approach and Diversion • Pattern Entry (Class D) • CTAF Operations • CTAF Operations – LC2L and Missed Approach • Preflight • Alternate Detailed Taxi Instructions & Following Traffic • LC2L During Taxi • Position and Wait & Ground Delay Program • Rejected Takeoff

The first three of the four tabletops employed a bowtie analysis method to structure the discussion and data collection [27-29]. This is an established process for qualitative risk assessment, supporting hazard identification following changes to operations. There are four steps to a bowtie analysis: first, a critical event or hazard is identified, then all possible causes for that hazard are identified, leading to the third step of listing the possible outcomes of the hazard. Finally, potential mitigations, both already existing and proposed future mitigations that may reduce the likelihood of the hazard are identified in the fourth step. These three tabletops were focused on the near and mid-term evolution of integrating autonomous air cargo into the NAS.

The goal for the fourth tabletop was similar to the first three in that the research team aimed to identify issues and solutions associated with specific scenarios or use cases, however, the scope now focused on the far-term phase of the evolution. Because participants were being asked to envision a concept further from current day, the method was altered to be more conducive to that effort. The Flexible Method for Cognitive Task Analysis (FLEX) was chosen as the basis for the fourth tabletop due to its specific application for developing future concepts [30]. For this method, the SMEs were separated into groups based on their area of expertise and then guided through a discussion aimed at providing solutions to issues that may exist when envisioning the future of the system. The issues and solutions from the first group were then taken to the second group for their feedback and/or alterations. Finally, the groups were brought together to discuss any lingering topics or areas where there were differing thoughts.

Assumptions about the UA's specifications, capabilities, onboard technologies as well as supposed level of automation were clearly defined for the participants at the start of their workshop. The purpose for this was to create a shared mental model to aid the moderator-guided discussions. However, participants had the opportunity to question and suggest alterations to the assumptions based on their perception of what might be feasible or necessary to safely conduct these types of operations. As an example, the assumed specifications for the UA during Tabletop 4 was that it was a UAS commercial cargo carrier operating under Parts 121 or 135, with similar flight capabilities to an ATR-42. The C2 link system was used for data exchange between the aircraft and the GCS regarding the flight operations of the uncrewed aircraft. This included, but was not limited to, flight control and related operational control instructions provided by the RP to be sent to the aircraft, and status and telemetry information from the aircraft to be sent to the RP regarding all aspects necessary for safe operations. Other assumed technologies for Tabletop 4 are listed below:

Doppler radar

- Provides wind shear alerts
- Displays significant convective activity

Flight Management System (FMS)

- Located at the GCS and on the UA to process and execute route and altitude requirements

Ground Proximity Warning System

Surveillance Equipment

- ADS-B In/Out
- Transponder
    - 4096 Capable
    - Mode C
    - Mode S
- Air-to-Air Radar

Visual Technology

- Provides a means of detecting the runway environment during takeoff and landing
- Provides means of detecting traffic, hazards, and obstacles during taxi
- Allows the RP visual reference for weather, other aircraft, or airborne hazards

Detect and Avoid (DAA) system

- Provides traffic with vector and altitude information on the GCS navigation display
- Provides alerting and guidance resolutions for well-clear and collision avoidance

Each tabletop built upon the resulting discussions of issues and solutions from the previous tabletop, at times delving deeper into a certain topic area and at others by adjusting the scope of the assumed environment and level of expected automation. The specific topics discussed during the individual tabletops can be found in Table A.1 above.

A.2 C2 and Communications Architectures

This Appendix subsection presents a summary of proposed near-term and an end-state concept C2 and communications architecture to support general UAS-NAS operations including concepts being researched and investigated by the PAAV project for air cargo UAS. This near-term/end-state approach assumes an initial architecture development effort (near-term) to form a core architecture and infrastructure. The near-term operational state introduces new functional elements, component capabilities and secure network interoperability that can be upgraded and modified in the future to form a far-term (end-state) configuration. The end-state architecture incorporates advanced PAAV concept identified in the far-term assumptions of Section 3.

In each architecture, multiple C2 systems are identified that individually, or in combination for a flight, would provide total UAS C2 link coverage. For C2 system management, system elements that enable seamless interoperability of these systems and manage connectivity for multi-remote pilot per UA flight and multi-UA piloting per remote pilot (i.e., m:N operations) are defined. The architectures are intended to operate in a general data-centric approach where UAS specific services and FAA services data and information are shared between users and accessible to all UA RPs. Functional elements are intended to identify a framework of an architecture that requires further research for eventual implementation.

Figures A.1 and A.2 below illustrate the near-term and end-State C2 and communications architectures.

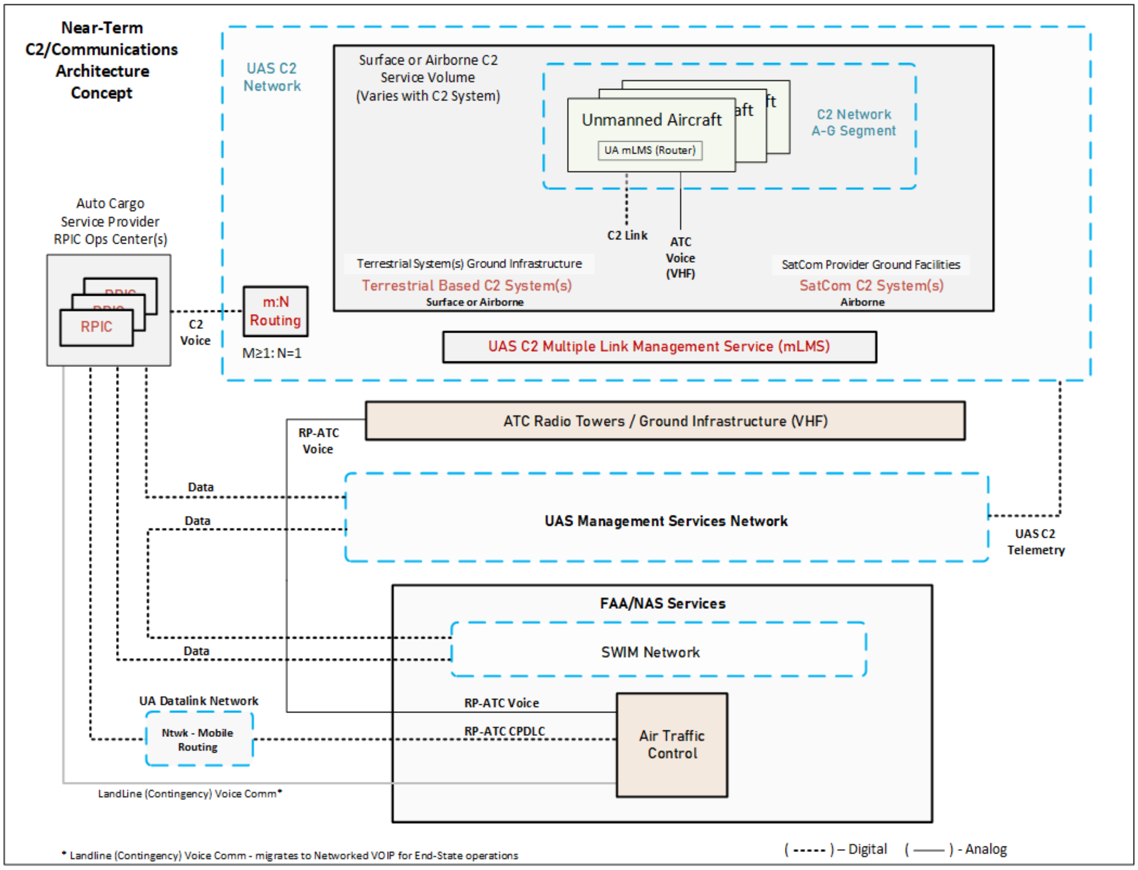


Figure A.1. Near-Term C2 and Communications Architecture

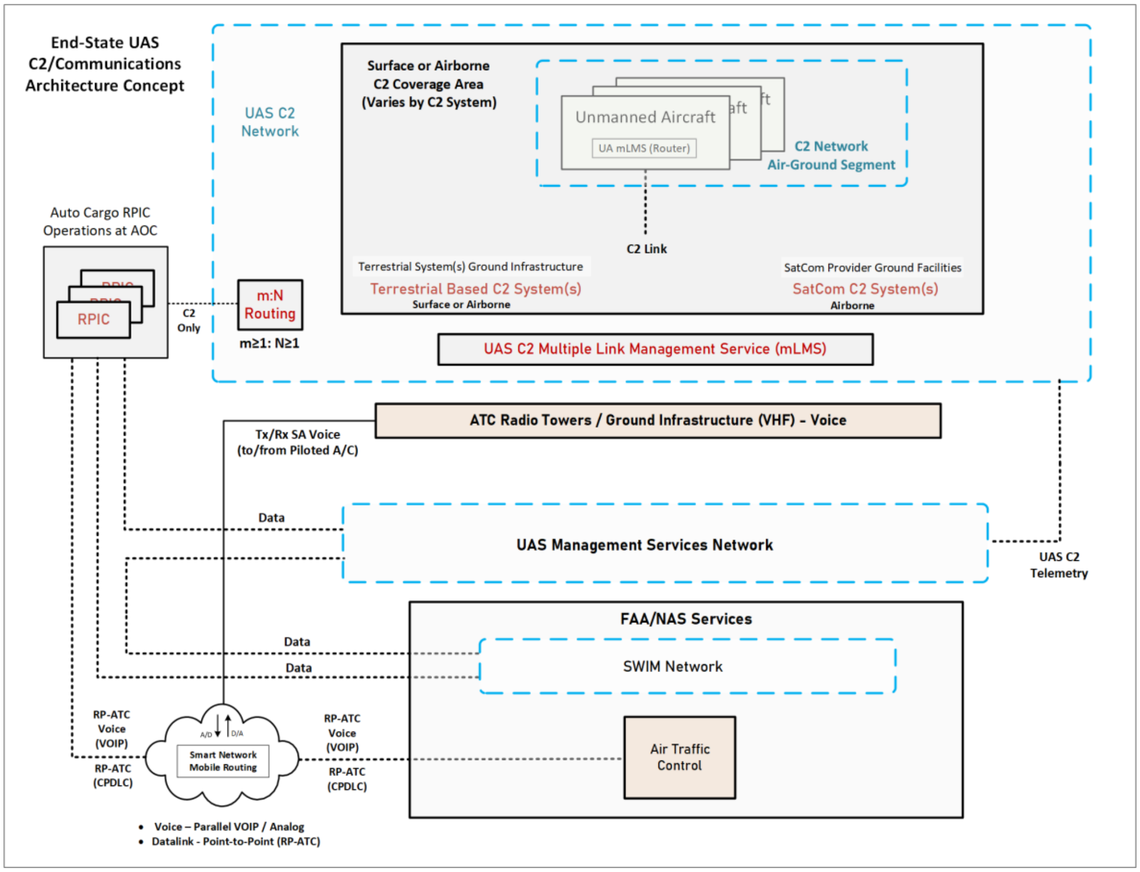


Figure A.2. Far-Term C2 and Communications Architecture

A.2.1 Functional Elements Description

C2 link systems - Both the near term and end state architecture propose multiple interoperable C2 link systems operated or deployed based on applicable or capable coverage areas, and largely dependent on terrain considerations for system supporting infrastructure. Where multiple systems could be used, decisions on system-in-use could be based on *best-performance-in-a-location* criteria.

The following three C2 system types are proposed:

1. Terrestrial Distributed C2 System - Ground-based system developed to meet the RTCA DO-362A, Command and Control Data Link Minimum Operational Performance Standards and RTCA DO-377A, Minimum Aviation System Performance Standards for C2 link systems. Functional role: Airborne Operations
2. Terrestrial Cellular C2 System* - Ground-based, wireless system based on LTE (4G or 5G) to provide C2 wireless connection to each UA via a distributed network of cellular towers. Functional role: Surface and Airborne Operations
3. Satellite-Based C2 System* – Satellite systems operated in Low-Earth or Geostationary Orbit (LEO or GEO) may be used to provide UA C2 communications where physical topography or other issues make ground-based infrastructure impossible or prohibitively expensive. These systems can provision simultaneous RF links from the satellite for connections to multiple UA within the satellite’s beam footprint, which can cover large regional areas. Functional role: Airborne Operations

   * Currently, no standards exist for Terrestrial Cellular or Satellite-Based C2 Systems.

UAS C2 Multiple Link Management Service (mLMS) coordinates inter-system operations (i.e., frequency allocations and sharing) for ensuring contiguous C2 link coverage for each UA flight. An mLMS is proposed in the architecture as a general UAS C2 service to provide UAS route, C2 service connectivity planning. The mLMS is envisioned as using flight plans submitted for each UAS flight to identify best available C2 systems coverage for a UA air-route. This service would operate interactively with RPICs, passing link and system plan information in real time. The service would assist with link problem resolution involving frequency changes.

A dedicated secure, high speed, high capacity, and resilient UAS C2 Ground/Air-Ground network is proposed for maintaining connections between the RP and the UA. Network endpoint hardware resides at each UA, RP site, link management service location, C2 GRS sites, and at Communication Service Provider (CSP) ground sites for SATCOM system connectivity. To manage information flow to multiple access points, this network model assumes mobile networking as an inherent capability for directing C2 link data to RP locations.

PAAV consideration of UA flights piloted by multiple RPs along a route and piloting operations that involve an RP managing multiple UA simultaneously (i.e., m:N operations) could take advantage of some form of intelligent routing component within the C2 network. This conceptual component is shown in each diagram above as an m:N Routing function block of the C2 network. This component is envisioned as using flight plan information and RP-UA assignments to plan C2 network connections for flight operations and would function to filter and route C2 traffic, voice traffic and data link traffic to provide more focused RP to UA communications. In the near-term, this component would be responsible for C2, data link and voice traffic routing between the RP and the UA for 1:1 operation, including the cases where the UA is handed off among multiple RPs along the route. As the m:N operations concept moves to RPs managing multiple UA, and RP-ATC voice communication moves to an advanced system using ground network digital voice, this function would continue to manage the C2 link connections for these m:N operations.

Voice and Datalink

- In the near-term architecture, the RP-ATC communications are proposed to be operated in a relay-through-the-UA approach. For voice communication, RP-to-ATC voice is digitized and transmitted over the C2 link to the UA. At the UA it is converted to analog for transmission over an ATC VHF radio to be received by ATC and any aircraft operating on a same frequency. For ATC to RP voice, ATC transmissions will be received by the UA VHF radio, digitized at the UA, downlinked via the C2 link, and transmitted over the ground network to the RP. This relay approach allows UA voice transmissions to behave similar to current piloted flight voice transmissions, maintaining party-line situation awareness in airspace. For data link communication, a new, dedicated ground network component that can direct messages between RPs and ATC – foreseen as being developed by a third-party provider – would supplement voice communication. These components would need to distinguish current UA-airspace location and responsible ATC, and dynamically direct data link traffic to appropriate end users (i.e., RP-ATC). Since data link is point-to-point, these messages are only communicated between the RP-ATC with no broadcast available.
- In the end-state concept, implementations of RP-ATC communications should transition to a system that uses digital voice (i.e., VoIP) and data link with technology upgrades occurring to the ground network component previously developed for data link. This approach would require an upgrade to the data link ground network component to dynamically direct voice and data link traffic to appropriate end users (i.e., RP-ATC). A system development effort would need to include a method for paralleling voice messages to the ATC GRSs operating in the current UA airspace. Using this type of system, many of the problems associated with combined latency of the C2 and ATC systems for RP-ATC voice communications can be eliminated while still complying with FAA preference for party-line, situation awareness.

UAS Management Services may be provided by third parties. Potential service examples include data processing and information services, UAS traffic management services, UAS fleet management services, and UA service provider operations support services.

The C2 and communications architecture should provide user (RP and UA management services) access to the FAA System Wide Information Management (SWIM) platform. SWIM is an information-sharing service that allows members of the aviation community to access specific information they need to efficiently run NAS operations. Access to SWIM data sets, including weather data, flight and flow data, aeronautical information, and surveillance, could be provided as a subscriber service to UAS users. This information could be valuable in their individual roles or to enhance data processing and information they provide within the data centric architecture.

A.2.2 Technical Challenges

Development of a standardized architecture for Command and Control and Communications for UAS operations that can accommodate PAAV objectives presents several technical challenges that will need to be met. These will include the following:

- Providing available Aviation Spectrum* for UA C2 systems, developing system standards, and developing these systems for validation.
- Minimizing C2 link delays.
- Developing fast, secure, and resilient networks for C2 and data and information sharing.
- Developing approaches for managing planned m:N operations.
- Developing alternate RP to ATC Voice and data link systems that reduce latencies and improve performance.
- Providing overall cyber security within a data-information centric architecture for UA C2 and communications.

* From ICAO World Radiocommunication Conference 2000 Proceedings - The International Civil Aviation Organization (ICAO), a specialized agency of the United Nations, has been developing standards since 1945. An important aspect of these standards relates to aeronautical radio communication, radionavigation and surveillance (radar) systems and equipment, installed on aircraft or on the ground. Aviation safety demands the availability and security of adequate and well-protected radio-frequency spectrum. ICAO has been actively working with ITU since 1947 to ensure that decisions related to spectrum management will secure the long-term availability of radio-frequency spectrum for aviation use.

A.3 Human-in-the-Loop (HITL) Simulation Study

A.3.1 Background

Due to the extra C2 link system network path distance that UA radio voice signals must go through to be transmitted on the FAA's ATC radio, there will be a voice delay in the RP-ATC voice communication. Note that the one-way voice delay is the interval between the time when the speech sound is uttered by the speaker and the time when the same sound is heard by the receiver. The voice delay does not include speech length or human operators' response delays.

The RTCA estimated the achievable one-way latency of the UA C2 link system to be 226 milliseconds (ms) for terrestrial link and 720 ms for geostationary-satellite-based SATCOM link (Appendix D in DO-377A [4]). With the expected delays for the NAS voice equipment added, the estimated one-way UA voice delay could be approximately 400 and 900 ms, respectively. Note that these are estimates for technologically achievable delays. In practice, UA can experience longer delays due to extended network path distance especially when on a SATCOM link.

The FAA's current requirements for voice communication latency between NAS users (e.g., pilot, air carrier) and the specialist (i.e., ATC) are less than or equal to 250 ms on average, less than or equal to 300 ms for the 99th percentile, and at maximum 350 ms [31]. There is additional known delay of 40 ms in the air propagation and onboard avionics. Thus, 390 ms is often referred to as the maximum acceptable voice communication latency within the NAS. The estimated UA voice delay (i.e., 400 and 900 ms) exceed the FAA's current maximum acceptable delay value. However, previous simulation studies reported that a UA one-way voice delay as long as 1,800 ms was rated acceptable by the ATC participants [32, 33]. Thus, there seemed to be a gap between the requirements and the empirical evidences. A potential explanation of lack of empirical evidence was that the traffic volume level in these studies were not high enough to observe the adverse impacts of the UA voice delay on the air traffic management (ATM) operations.

A.3.2 Method

A PAAV laboratory HITL simulation study was conducted in the Airspace Operations Laboratory (AOL) and the Human Autonomy Teaming (HAT) Laboratory at NASA Ames Research Center between August 17 and September 10, 2021. The study evaluated the effects of the UA RP's voice delays on the ATM operations. The main hypothesis was that the negative effects of the UA voice delays on the en-route ATM operations are larger when the background traffic volume is higher rather than lower. This hypothesis can be investigated by the statistical significance level of the interaction effect of the voice delay and traffic volume level. The experiment design was 3 x 2, including three voice delay lengths and two traffic volume levels.

The three one-way UA voice delay lengths tested were 400 ms, 900 ms, and 2,000 ms. The three delay values represented the delays associated with the terrestrial C2 link system latency, the SATCOM C2 link system latency, and a longer SATCOM C2 link system latency, respectively.

The high and low traffic-volume levels reflected approximately 110% and 66% of the Monitor Alert Parameter (MAP) traffic level, respectively, of the Oakland Air Route Traffic Control Center (ZOA) combined sectors 40 and 41.

The combined sectors 40 (surface to 8000 ft) and 41 (8000 ft to FL 230) was controlled by one en route ATC. A single UA—with a call sign, NASA01—departed from the Metro Oakland International Airport (KOAK) and arrived at the Ukiah Municipal Airport (KUKI), 96 nmi Northwest of KOAK, on an IFR flight plan. At the KUKI, a non-towered airport, NASA01 performed the area navigation (RNAV) (GPS)-B runway 33 approach, executed a Missed Approach at the Decision Altitude, and contacted ZOA 40/41 again for being re-vectored to the same approach. Each scenario started from the time when NASA01 entered ZOA 40/41 while on an initial climb from KOAK and ended at 46 minutes elapsed, when NASA01 was being re-vectored to intercept the final approach course.

To simulate the traffic scenarios, Multi Aircraft Control System (MACS) in the AOL and the VSCS in the HAT Lab were networked via Live Virtual Constructive Distributed Environment (LVC-DE) and Aeronautical Data Link and Radar Simulator (ADRS). MACS generated background cooperative traffic (equipped with transponder or ADS-B) and emulated one ZOA 40/41 ERAM station (Figure A.3, left), three pseudo pilot stations, one ghost ATC station, and one ghost pilot station. VSCS emulated the UA RP GCS workstation (Figure A.3, right), including the DAA alerting and guidance functions, and one non-cooperative traffic that caused a scripted traffic conflict with NASA01 and forced DAA alert events. The non-cooperative traffic was not visible on the ATC's scope but visible only on the RP's. Thus, the RP had to initiate the ATC radio communication to request the traffic avoidance maneuvers.

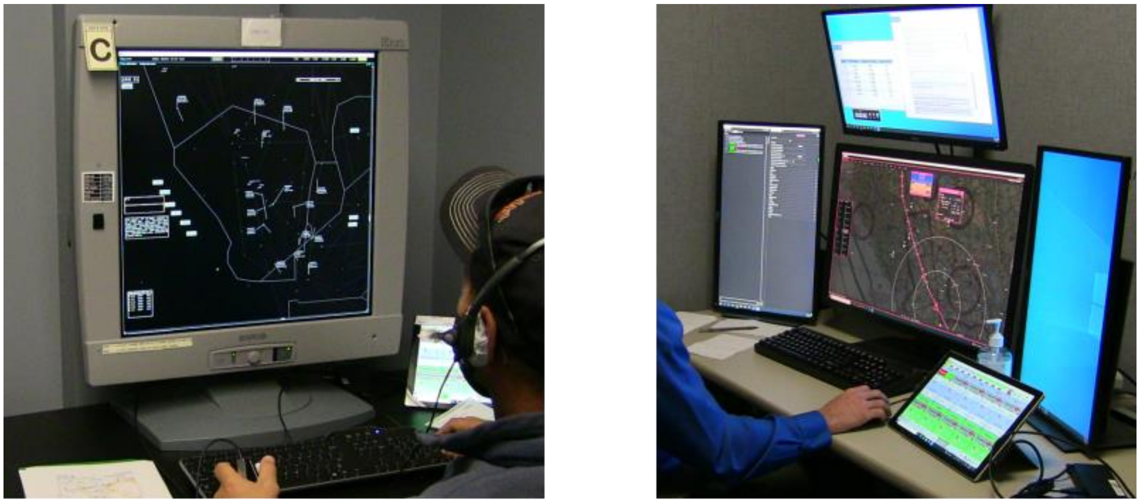


Figure A.3. ATC Workstation (Left) and RP Workstation (Right)

Eight ZOA ATCs, eight RPs, and three pseudo pilots (PPs) participated in the study. One ATC and one RP were paired and participated together in a two-day data-collection session. Each two-day session started with training runs in the morning followed by six runs in the rest of the two-day session. Each pair of an ATC and an RP experienced all the 3 (voice delays) x 2 (traffic volume levels) combinations. The run orders were counterbalanced within and between the participant pairs. In total, 48 runs were conducted in 16 days. The three PPs supported all the data-collection sessions. Two PPs controlled the ZOA background traffic, and one the KUKI CTAF traffic.

A.3.3 Main Findings

The results showed the following negative effects of 2,000 ms UA voice delay in comparison to 400 and 900 ms voice delay, regardless of the background traffic volume level:

- The number of radio transmission step-ons increased.
- The DAA Corrective Alerts for the scripted non-cooperative traffic conflict were more likely to elevate to a Warning Alert level.

The first finding, the increased step-ons, was consistent with the previous studies' reporting [32, 33]. The second finding, the increased numbers of DAA alert level elevations, was caused by the increased step-ons and/or being unable to find a gap on the radio to begin speaking.

The study also detected some interaction effects of voice delay and traffic volume levels being statistically significant, which was the primary interest of this study. The following negative effects were statistically significant only when the voice delay was 2,000 ms and the traffic volume was high, but not in the other combinations.

- The ATCs' workload ratings increased.
- The ATCs adjusted their communication strategy to accommodate the UA voice delay.
- The ATCs' acceptance for accommodating additional UA with the same voice delay characteristics in the sector decreased.
- The ATCs indicated that the UA voice delay was disruptive for the ATM operations.
- The RPs' acceptance for the DAA alerting and guidance for remaining DWC decreased.

The overall effects of the UA voice delay observed were small in magnitude, but likely underestimated due to simulation artifacts, such as that our PPs behaved more patiently than pilots in busy airspaces. If the 2,000-ms UA voice delay under high traffic volume condition already exhibited measurable adverse effects in this laboratory simulation, it is likely that the voice delay effect would be even greater in real operations. Therefore, remedies such as increased separation buffers or restricted background traffic density should be considered.

For the 400- or 900-ms UA voice delays, no major adverse effect was found in this study; however, these delays still exceed the FAA's current requirement for the maximum voice delay in the NAS (i.e., 390 ms), and require further evaluations. The present study's findings may offer grounds for cautious optimism that the background sector traffic level may be used as a control variable to carefully raise the safety threshold for the UA voice delay under low traffic density conditions.

More details of this HITL simulation study can be found in [16].

A.4 Numerical Simulation Studies

In a typical scenario with UA, separation assurance functions could be divided among three major agents: the ATC controller, the RP, and the UA. Depending on the type of automation and delegation, there are several pairs of communication, like controller-RP and RP-UA, and other intermediate agent level sub-functions. Each of these entails a potential response time (latency) and/or disruption (reliability) which would impact the overall performance of the separation assurance function. In an airspace, safety may decrease as the number of UA increases. Additionally, it is expected that an increase in latency and decrease in reliability will also have a significant impact on safety. A baseline study was conducted to investigate the impact of latency and reliability on separation assurance with RPA operating amidst crewed aircraft traffic in a generic terminal arrivals environment. The study focused on the response time between a controller determining the resolution and detecting that the RPA has begun implementing the resolution.

Two types of UA were studied: ATR-72 and Cessna-208. Input data was produced with 100 flights in each scenario in a generic terminal arrival environment with three merging arrival flows, designed for the study. The number of UA among those 100 was varied to simulate increasing mix of UA traffic. Three UA traffic mix were tested: 10, 30 and 50 UA. In each scenario, the aircraft type used as UA were kept homogeneous while the aircraft types for background legacy traffic were selected based on traffic data into regional airports. For a given RPA type and traffic mix, five values of response time (RT) (between 0 and 120 seconds) and six values of message drop probability (MDP) (between 0 and 0.5) were studied, for a total of 180 simulations. A fast-time simulation methodology was developed and used to conduct the study. Losses of separation and arrival delays in each test scenario were measured.

Results showed that, the safety of the system degraded as the response times and MDP values were increased. Overall response times under thirty seconds and messages dropped with a probability less than 0.2 exhibited the least impact on safety. The level of degradation depended on the type of RPA with Cessna scenarios generally performing better than ATR scenarios. The system efficiency measured by arrival delays observed, exhibited a counter-intuitive response with reduction in delays at high RT and MDP values. However, closer inspection showed that these reductions came at the cost of safety and losses in energy costs. This provided further insights into the dependency on the aircraft flight characteristics and the effects on ATC-UA interaction with delayed and missed messages.

This work was published as a paper titled "Impact of Latency and Reliability on Separation Assurance with Remotely Piloted Aircraft in Terminal Operations", presented at the AIAA Aviation 2022 Forum [17]. The paper examined the effects of latency and reliability on separation assurance without any compensating measures and thus serves as a baseline for further studies that can examine alternative solution concepts (mitigation strategies) and their trade offs. Certain mitigation strategies, for example, onboard DAA systems, could minimize the need for ATC-UA communication with more separation responsibility on board. A higher fidelity breakdown of the response time with focus on individual communication links was also identified as a direction for further exploration. The work presented was also a first step towards developing both an understanding and a test environment to conduct more detailed studies that measure impact at increasing levels of autonomy in the airspace. These may include delegating separation responsibility to the UA or RP from ATC. These could also include increased automation of RP and ATC tasks and increasing the number of UA (N) that are managed by the number of RPs (m). While this paper focused on an RP:UA ratio of 1:1, the test apparatus is being augmented to simulate m:N scenarios wherein a few RPs operate several UA.

A.5 Function Allocation

A pair of functional allocation papers was presented at the AIAA Aviation 2022 Forum entitled "A Framework for Dynamic Architecture and Functional Allocations for Increasing Airspace Autonomy" and "Functional Allocation Approach for Separation Assurance for Remotely Piloted Aircraft" [34, 35]. The purpose of these two papers was to present an autonomy framework for decomposing and allocating the functions necessary for safe, orderly, and expeditious flight among the human and automation agents of a remotely piloted aircraft system and to present an example of the functional allocation process for the function of separation assurance. The framework, extended from previous decomposition processes [36, 37], was extended to capture the dependence of the functional allocation on the system architecture (e.g., the RP to UA ratio, m:N) and on the operational context (e.g., LC2L). The framework is intended to help determine which functions should, and can, be allocated to automation and human agents (e.g., the UA and the remote pilot) to enable scalable m:N operations under nominal conditions and safe and predictable operations under off-nominal conditions, particularly LC2L. The framework was applied to the separation assurance functional allocation example to highlight the dependency of the functional allocation on three criteria: time criticality, m:N, and LC2L. A brief overview of the functional decomposition and allocation process will be presented below.

The functional decomposition process is performed to break down an abstract function into finer components that match human cognitive models or other similar breakdowns [34]. There are four steps to the functional decomposition process, colloquially termed IISA [37]:

1. **Information Acquisition (I):** Acquiring the information needed for performing the function.
2. **Impact Assessment (I):** Assessing the information to identify any problems and their impacts.
3. **Solution Planning (S):** Planning solutions to mitigate the problems and their impacts.
4. **Action Implementation (A):** Implementing the solutions by taking the appropriate actions.

Once the function has been decomposed, the agents capable of executing the function must be determined. These agents, the decomposed function, and their inter-relationships, are assessed along levels of autonomy. The operational context, such as weather, will also impact the complexity and uncertainty of the function, thereby affecting the allocation to the agents. Finally, the allocation process is also dependent on several allocation criteria, such as time criticality, that indicate that the allocation process must be dynamic. That is, no one single allocation necessarily works across all possible architectures and with all agents at all times.

In the examples presented below, the separation function is analyzed. This separation function has been abstracted to all activities with the goal of preventing loss of safe distance between vehicles, irrespective of the performing agent, including ATC separation, pilot detect and avoid (DAA), vehicle collision avoidance, among others.

A.5.1 Allocation Dependency on Time Criticality

An example high-level allocation process relating to the function of separation assurance is presented in Figure A.4. Figure A.4 shows a series of possible functional allocations along a timeline towards a potential conflict between two UA that are remotely piloted. These UA are operating under IFR and the allocations are with respect to the ownship, not the intruder. Also note that this example only considers the dependency of the functional allocation on time criticality. Similar dependencies exist on the complexity of the airspace and the traffic situation, such as interactions with VFR aircraft and flying under IMC or VMC conditions. These other dependencies are not discussed in this examples.

Three allocations are shown at three time horizons from the conflict (note that this time discretization is an example and more allocations along the time are possible). While three time horizons are shown, it should be noted that an allocation closer to the conflict is considered only if the conflict was not resolved successfully by an earlier allocation to the left of it. The first row of allocations applies to a 1:1 pilot to vehicle ratio in a nominal context. The second and third rows show adjustments to the allocations under m:N nominal operations and under LC2L, respectively. Each allocation is shown in a tableau with the agents as columns and the IISA tasks as rows. The agents include ATC (representing the ASP for separation), automation of ATC (AUT), RP, automation on the ground control station (GCS), and UA. The role of each agent in each task is shown as one of three levels: primary, secondary and none. The primary role, shown as black color, refers to having authority to perform the task. The secondary role, shown as grey color, refers to assisting in the task, either in a shared/cooperative capacity, in a supervisory/delegated capacity, or in an oversight capacity. No role at all is shown as white color. In the examples presented here, it is important to note that the changes in roles are changes in authority, but not in responsibility. Changes in responsibility are not addressed in this example.

Under a 1:1 architecture with nominal conditions, ATC can assume the primary role when the conflict is far enough in the future that sufficient time is available to acquire the information, assess and resolve the conflict. Automation similar to that which has been proposed for crewed flights could have added benefits when utilized for UA. For example, automation may be needed to alert ATC that one or both of the vehicles is a UAS, which implies potentially more latency in its response to ATC instructions, especially if the UA is using satellite for C2 and communication. Automation may also assist ATC in predicting the future conflict and in resolving the conflict using closed trajectories and priorities that are tailored for the UA behavior. The primary role in implementing the resolution is given to the UA (by necessity since the conflict cannot be resolved unless the UA maneuvers). ATC, RP, and their associated automation have a necessary secondary role to communicate and command the resolution maneuvers. Some additional research questions revolve around: Is there a need for an assistive role by the RP and GCS, in providing information, assessments, or suggested solutions to ATC? For example, the RP can supply ATC with additional information about the UA maneuvering limitations, risks due to any observed C2 link degradation, or particular trajectory solutions that are preferred for the UA. Such RP assistance and coordination is expected to be more critical for large route deviations that may take the UA outside a reliable C2 coverage area. Meanwhile, guidelines could be created that state the UA should be capable of maneuvering a prescribed distance from its nominal route to accommodate most ATC vectors, corresponding to an area that would be expected to have reliable C2 link coverage. As time to the conflict decreases, the primary separation assurance role moves to the RP who performs self-separation with assistance from the GCS. The motivation for this is that time is more critical such that there is not sufficient time for ATC to assess a conflict and communicate a resolution. In this phase, airborne or ground-based DAA technology is needed to assist the RP. The implementation of the resolutions remains the primary role of the UA with the RP assisting by delivering the commands through the GCS. ATC continues to play an assistive secondary role, such as providing situation awareness about surrounding traffic to the RP's who maintain the responsibility to separate. Some research questions in this phase revolve around: Is it necessary to have an assistive role by the UA automation to supplement ground-based automation, in providing information, assessments, and/or suggested solutions? For example, an airborne DAA system may provide alerts over a sufficiently large range supportive of self-separation in this time horizon.

Finally, as the vehicles get even closer to the conflict, the primary separation assurance role moves to the UA because there is no time for the RP to react. Reliance shifts to be on the UA automation (such as airborne DAA or collision avoidance technologies) with possible assistance from the ground-based automation (such as a ground-based DAA system), which may be needed to supplement the accuracy and reliability of the airborne system. Some questions here revolve around the following questions: At what point in time does reliance on the RP in a primary role stop being safe, meaning the UA must avoid collision autonomously with only optional assistance from the RP? Does the RP maintain the ability to monitor and intervene in a supervisory role and for how long can the RP maintain this ability before it becomes prohibitive to do so and they must trust that the UA is acting appropriately? If the UA has the authority, should the RP remain responsible for the actions of the UA?

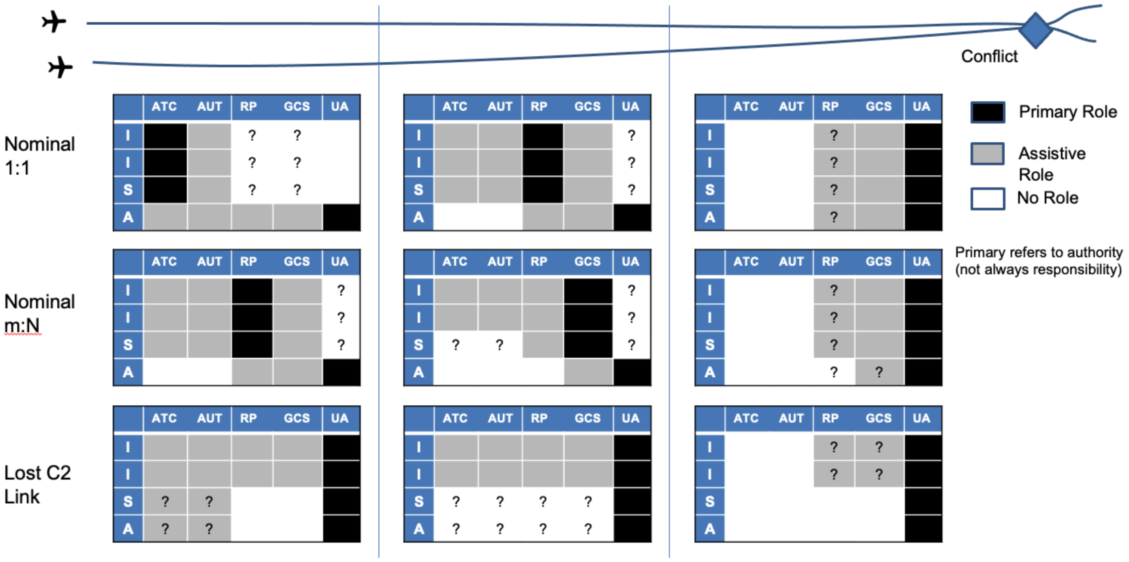


Figure A.4. Dependency of Separation Function Allocations on Time Criticality, m:N Ratio, and LC2L

A.5.2 Allocation Dependency on m:N

With an m:N architecture where the RP is operating multiple UA simultaneously under nominal conditions, ATC may not be able to assume the primary role even when the conflict is far in the future because the delay in the RP response (while handling multiple UA) precludes the ability of ATC to acquire the information and assess and resolve the conflict in a timely manner. Moving the primary separation assurance role to the RP is one mechanism to enable m:N operations by performing self-separation rather than depending on ATC. However, automation is needed to assist the RP who is handling many UA and is already busy with supervising their aviate and navigate functions. Automation assists the RP in predicting and resolving the conflict. The primary role in implementing the resolution is given to the UA by necessity, with assistance from the RP and GCS automation to communicate and command the resolution maneuvers. Some additional research questions revolve around: Moving the primary role to RP may need regulatory support. While it is assumed that UA will operate under IFR initially, future UA operations may utilize tailored flight rules that facilitate increasingly autonomous operations (e.g., Digital Flight Rules [14] or Digital VFR). What role does ATC maintain, such as assisting in situation awareness about surrounding traffic and sharing conflict assessments, potentially even suggesting resolutions? What is the role of GCS and UA and what are the minimum levels of automation needed in the GCS and the UA to enable RP self-separation while operating many UA? Is there a need to expand on the detect and avoid technology to support the RP in self-separation over a long time horizon? As time to the conflict decreases, the primary separation assurance role moves from the RP to the GCS with assistance from the RP. The motivation is that time is more critical such that there is not sufficient time for the RP, who is handling many UA, to predict, assess and resolve conflicts. In this architecture, automation is needed for information acquisition, impact assessment, and solution planning to enable m:N operations. The automation can be in the GCS rather than on the UA if the C2 link is assumed to be working and reliable, though onboard redundancies would of course be necessary. In this phase, detect and avoid technology—airborne and/or ground-based—may be used not only to advise the RP, but also to plan and execute resolutions in which the RP may play a supervisory or simply an oversight role. The implementation of the resolutions remains the primary role of the UA with the GCS assisting by delivering the commands. There are some additional research questions in the phase: How is trust in the GS and UA automation achieved and what is the required role of the RP in terms of providing supervision and oversight of the automation depending on the trust in the automation? When moving the primary role to GCS automation, does the RP stay responsible for the GCS actions? What role does ATC maintain and can ATC automation directly support the GCS and UA automation without human involvement? Finally, as the vehicles get even closer to the conflict, the primary separation assurance role moves to the UA because there is no time for the GS to react and send the information or resolution to the UA. This involves still more research questions: When moving the primary role to the

UA automation, does the GCS automation still assist and how (e.g., by providing ground-based situation awareness to the UA)? Can RP still assist, or must they trust that the UA is acting appropriately?

A.5.3 Allocation Dependency on LCL2 Context

Under LC2L conditions, neither ATC nor the RP can command the UA and resolve a conflict, at any time horizon. Ensuring safe operations under LC2L necessitates that the UA automation maintains the primary role and authority for separation assurance. While there are assistive roles ATC and the RP can play (e.g., alerting other traffic to the presence of a UA in a LC2L state and its probable course), there are limitations to these roles. Even if ATC assisted by separating the other traffic under their control from the UA, there still exists a need for the UA to self-separate, especially from non-cooperative VFR traffic and from other UA's simultaneously under LC2L. As time to conflict decreases, the ability of ATC to assist in the situation decreases. Thus, the ATC function diminishes to solely raising situation awareness and eventually may disappear, as shown in Fig. A.4. The RP (and GCS), on the other hand, cannot have a role in the solution planning and action implementation steps, given the lack of link to the UA. They can assist in raising situation awareness of ATC and of other pilots and RPs by sharing relevant information and impact assessments through alternate communication links. Some research questions here are the following: How can predictable LC2L behavior be ensured? What assistance can ATC and RP provide to UA in LC2L conditions? For example, can they share situation awareness with other traffic and move other aircraft away from the UA's anticipated flight path? As depicted in the tableaus in the figure, their ability to assist diminishes as time to the conflict decreases, and hence complete reliance on the UA's self-separation capabilities becomes more critical.

Appendix B: Acronyms and Abbreviations

Acronym	Definition
A&ER	Automation And Emergency Recovery
AAM	Advanced Air Mobility
ABRR	Airborne Reroute
ACAS Xu	Airborne Collision Avoidance System for Unmanned Aircraft
ADRS	Aeronautical Data Link and Radar Simulator
ADS-B	Automatic Dependent Surveillance-Broadcast
AFRL	Air Force Research Laboratory
AGL	Above Ground Level
AIM	Aeronautical Information Manual
AOC	Airline Operations Center
AOL	Airspace Operations Laboratory
AOSP	Airspace Operations and Safety Program
ARTCC	Air Route Traffic Control Center
ATAR	Air-to-Air Radar
ATC	Air Traffic Controller
ATCT	Airport Traffic Control Tower
ATM	Air Traffic Management
ATM-X	Air Traffic Management - eXploration
AUT	Automation of ATC
BNE	BVLOS NAS Evaluation
BVLOS	Beyond Visual Line of Sight
C2	Command and Control
CNPC	Control And Non-Payload Communication
CNS	Communication, Navigation and Surveillance
COA	Certificate of Waiver or Authorization
CPDLC	Controller-Pilot Data Link Communication
CSP	Communication Service Provider
CTAF	Common Traffic Advisory Frequency
CTOL	Conventional Takeoff and Landing
DAA	Detect and Avoid
DLR	German Aerospace Center
DWC	DAA Well Clear
EDST	En Route Decision Support Tool
ERAM	En Route Automation Modernization
EUROCAE	The European Organisation for Civil Aviation Equipment
FAA	Federal Aviation Administration
FLEX	Flexible Method for Cognitive Task Analysis
FMS	Flight Management System

Acronym	Definition
FOC	Flight Operations Center
FTI	FAA Telecommunications Infrastructure
GBSS	Ground-Based Surveillance System
GCS	Ground Control Station
GEO	Geostationary Orbit
GPS	Global Positioning System
GPWS	Ground Proximity Warning System
GRS	Ground Radio Station
GSO	Ground System Operator
HARS	High Altitude Relay System
HAT	Human Autonomy Teaming
HITL	Human-in-the-Loop
HMD	Horizontal Miss Distance
IAP	Instrument Approach Procedure
ICAO	International Civil Aviation Organization
IFR	Instrument Flight Rules
ILS	Instrument Landing System
IMC	Instrument Meteorological Conditions
KOAK	Metro Oakland International Airport
KUKI	Ukiah Municipal Airport
LC2L	Lost C2 Link
LEO	Low-Earth Orbit
LMI	Logistics Management Institute
mLMS	Multiple Link Management Service
m:N	Multiple Operators per Multiple UA
MACS	Multi Aircraft Control System
MAP	Missed Approach Procedure; Monitor Alert Parameter
MASPS	Minimum Aviation System Performance Standards
MDP	Message Drop Probability
MOA	Military Operation Area
MOPS	Minimum Operational Performance Standards
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
OPD	Optimized Profile Descents
PAAV	Pathfinding for Airspace with Autonomous Vehicles
PIC	Pilot in Command
PSU	Provider of Services to UAM
RA	Resolution Advisory
RAD	Route Amendment Dialog
RF	Radio Frequency

Acronym	Definition
RNAV	Area Navigation
RP	Remote Pilot
RPA	Remotely Piloted Aircraft
RPAS	Remotely Piloted Aircraft Systems
RPIC	Remote Pilot in Command
RT	Response Time
RTC	Return to Course
RTCA	Radio Technical Commission for Aeronautics
RWC	Remain Well Clear
SATCOM	Satellite Communication
SID	Standard Instrument Departure
SME	Subject Matter Expert
STAR	Standard Terminal Arrival Route
SUA	Special Use Airspace
sUAS	Small UAS
SWIM	System Wide Information Management
TAM	Tailored Arrival Manager
TCAS	Traffic Alert and Collision Avoidance System
TFMS	Traffic Flow Management System
TIS-B	Traffic Information Services - Broadcast
TMI	Traffic Management Initiatives
TPI	Traffic Pattern Integration
TRACON	Terminal Radar Approach Control
UA	Uncrewed Aircraft
UAM	Urban Air Mobility
UAS	Uncrewed Aircraft System
UNFO SP	UAS National Airspace System Flight Operations Standard Procedures
VFR	Visual Flight Rules
VHF	Very High Frequency
VMC	Visual Meteorological Conditions
VoIP	Voice Over Internet Protocol
VSCS	Vigilant Spirit Control Station
VTOL	Vertical Takeoff and Landing
xTM	Extensible Traffic Management
ZOA	Oakland Air Route Traffic Control Center

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