Remote Pilot Handoffs in Large UAS Multi-Vehicle Operations: Best Practices and Supportive Technologies

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***Abstract*—In response to pilot shortages and increasing air cargo demands, NASA's Pathfinding for Airspace with Autonomous Vehicles (PAAV) sub-project conducted the fourth in a series of tabletop studies investigating scalable solutions for integrating large Uncrewed Aircraft Systems (UAS) into the National Airspace System (NAS). This study solicited subject matter expertise to identify solutions to potential challenges for a further term vision, guiding participants through scenario-based discussions where the remote pilot (RP)-to-vehicle ratio has been scaled from 1:1 to m:N. Of those challenges, remote pilot handoffs were found throughout all phases of flight, both in nominal and non-nominal scenarios. The current paper details participant-suggested procedural and technological solutions for overcoming the handoff challenge, including determining the accepting RP, which aircraft to release, the location and timing of the transition, and options for supporting personnel, tools, and automation that could facilitate safe and efficient handoffs.**

Keywords—m:N operations, multi-vehicle operations, handoffs, load-shedding, Uncrewed Aircraft Systems (UAS), human factors, workload, future airspace management

I. Introduction

The direction of airspace operations research is evolving with an increasing eye towards uncrewed and autonomous flight. Domestic U.S. cargo and passenger operations are predicted to increase by 2.6 percent by the year 2042 [1] while the demand for pilots is expected to increase in a similar timeframe [2]. With the expected operational increases and global pilot shortages in mind, the Pathfinding for Airspace with Autonomous Vehicles (PAAV) subproject within the National Aeronautics and Space Administration (NASA) Air Traffic Management - eXploration (ATM-X) project, is developing a roadmap that aims to detail a pathway towards the seamless integration of Uncrewed Aircraft Systems (UAS) operations in the National Airspace System (NAS) [3]. This roadmap anticipates that the transition to fully autonomous flight for large UAS will continually unfold as technology matures and regulation allows, with multi-vehicle operations serving as a an interim phase between a 1:1 pilot-to-aircraft ratio and fully autonomous flight. Also known as m:N (read "m-to-N"), this construct is defined by allocating multiple UAS ("N") to be simultaneously controlled or supervised by a smaller number of remote pilots ("m"). To understand how automation might be leveraged, a classification framework [4] can be used to assume a locus of control and level of autonomy for these flights. For m:N operations, this is expected to reside within the range of shared or supervisory automation and more or less delegated control (Fig. 1).

Automation Levels

Human → Shared → Supervisory → Fully Automated

Control Locus Levels

Centralized → Collaborative → Delegated → Distributed with Oversight → Fully Distributed

Fig. 1. Five levels of automation and control locus.

Advancements in UAS research and development, including robust command-and-control (C2) links [5, 6] and increased automation through strides in technology, has given way to the viability of the m:N remote pilot (RP)-to-aircraft ratio. However, as the shift from near-term (1:1) control to m:N control occurs, the piloting role will also evolve, necessitating investigation into potential impacts on an RP's cognitive resources and the best practices and technologies to support their changing tasks and responsibilities.

Previous research on m:N and an RP's ability to control multiple vehicles simultaneously has supported the need to address situation awareness and workload concerns to allow m:N to scale to a profitable level. However, research into decision support tools [7], automation-allocated tasks [8], and improved display formats [9] demonstrates that concerns about operator performance can be addressed by leveraging existing or new tools. Furthermore, results from development and testing specific methods for performing aircraft handoffs [9, 10] has shown to offer additional avenues for improving performance during that critical point in the flight. Although versions of specific tools have been successfully tested in simulation, the full range of possible interventions upon the UAS, RP, automation, and support personnel as a complete and symbiotic system is difficult to investigate at this early stage of concept development. Three recent studies [11] endeavored to address the system as a whole by using a tabletop and bowtie analysis [12] format to generate mitigations to potentials hazards when integrating large cargo UAS into the NAS; however, these studies were not designed to investigate this within the m:N context.

When imagining how uncrewed aircraft (UA) would be allocated to RPs, a straightforward option for RP-to-UA assignment would be to follow the current day standard, where crews are in the cockpit and in control, end-to-end, for the entire duration of a flight. If following this paradigm, the events that would trigger UA reassignment would be contingency situations where the operator might elect to load-shed of one or more assets as their workload threshold reached a maximum. Although it may seem logical to follow familiar practices with the end-to-end approach, there could be drawbacks regarding cost and efficiency if RPs are assigned all flights before takeoff and retain control until landing. In order to reach the efficiency and profitability that m:N proposes, flights would have to be found that both begin and end during an RP's shift, and if those assigned flights are not geographically similar, then an RP's workload to acquire and maintain sufficient situation awareness of the area would likely increase, possibly leading to a lower maximum "N".

With an eye towards scalability, a phase-based strategy for delegating RP-to-UA assignments was assumed for the current study, such that individual flight segments would be divided by location and phase of flight. In this option, RPs would be assigned flights within a limited set of locations and a single phase such that there would be a dedicated ground, terminal, and en route RP for each flight. This would alleviate the added workload from gaining awareness of the area, including the weather, current routes, and traffic levels. However, there are also drawbacks to this approach, primarily that RP handoffs would occur regularly mid-flight, a departure from traditional end-to-end control. Thus, when considering the feasibility of these m:N operations, RP workload management, specifically in regards to the cognitive demands placed on operators during planned and unplanned handoffs is a critical challenge to overcome. Facilitating the positive transfer of situation awareness in a safe and timely manner may be influenced by assumptions made about the m:N architecture, procedures, support personnel, and available tools and technologies on the UA and at the Ground Control Station (GCS).

A. The Current Study

To further explore the m:N concept, members of the research team conferred with members of the RTCA SC-228 Large UAS m:N working group [13] to develop themes for a semi-structured tabletop study with pilot, dispatcher, and air traffic control (ATC) subject matter experts (SMEs) [14]. The goal of the study was to provide participants with a strategically organized method to discuss solutions, not only to generate one-off ideas for singular issues, but to develop complementary solutions to alleviate multiple issues at once. During guided discussions of detailed scenarios encompassing the full range of flight phases, participants were asked to imagine the most appropriate RP roles (e.g., ground, terminal, and en route) and m:N ratios for a variety of events. Among other challenges, participants were asked to review the issue of UA being handed off to a second RP, either as part of nominal transition procedure, or during non-nominal events. Although targeted scenarios on this topic were limited to handoffs due to specifically scripted planned events (e.g., entering or exiting Terminal Radar Approach Control facilities (TRACON)) and unplanned events (e.g., C2 link disruption) additional handoff discussions were organically initiated during the other prepared scenarios. The current paper presents participant-generated best practice and technological solutions for the handoff challenge, a selection of the final results from eight days of data collection. These solutions have been organized into four categories: (1) determining who should receive a handoff, (2) which UA should be handed off, (3) where or when handoffs should occur, and (4) how automation, support personnel and GCS tools might be designed to improve RP situation awareness and workload when initiating or accepting a UA handoff.

II. Methods

A. Data Collection

An adaptation of the Flexible Method for Cognitive Task Analysis (FLEX) technique [15] was used to structure the discussions of the fourth tabletop study. Because the FLEX method was designed specifically to explore future concepts, researchers chose this technique over the bowtie analyses employed for the previous tabletop studies that had a more near-term focus. SMEs were grouped by their area of expertise before being led through separate guided discussions on m:N scenarios and concepts. Three sessions with two SME groups were held over 8 days. The two initial sessions both began with an introduction to the problem space and a walkthrough of baseline UAS and m:N assumptions. The first session occurred over four days and included pilots and a dispatcher, the second session occurred over three days and included ATC participants. The third and final session concluded with a single day of combined group discussion. The study was conducted remotely via Microsoft Teams in May of 2022.

B. Participants

A total of 13 SMEs participated in the study, chosen based on their professional experience and qualifications. Three commercial pilots, three remote pilots, and one dispatcher comprised group 1, while six air traffic controllers comprised group 2. All ATCs were Certified Professional Controllers (CPC) with total certified years ranging from 9-34 years ($M = 28.72$). Four of the ATCs had tower experience, five had TRACON experience, and four had Air Route Traffic Control Center (ARTCC) experience. All commercial pilot participants had Airline Transport Pilot (ATP) licenses with instrument and multi-engine ratings. Remote pilots had a combined 6,085 hours of UAS experience, with a majority (5,800) of those hours flying MQ-9 aircraft. The sole dispatcher participant was licensed with 43 years of combined and overlapping professional experience with Part 121 and 135 operations.

C. Assumptions

1) m:N Architecture

Overviews of the m:N concept and purpose were explained to participants before sessions began. Participants were shown example m:N configurations but were encouraged to challenge these assumptions during discussions to improve the concept for Large UAS navigating the NAS. These notional RP-to-UA ratios depicted 1:2, 1:5, and 2:5 configurations with RP roles based on phase of flight; either ground, terminal, or en route (Fig. 2, 3 and 4). The assignment of RPs to UA, whether by area or in sequence, was intentionally undefined by researchers to allow wider feedback on best practices. A briefing on RP-to-RP handoffs—i.e., the transfer of control of one or more vehicles from one RP to another—included a brief discussion on handoffs due to planned and unplanned events.

2) Uncrewed Aircraft System (UAS)

Participants were briefed on starting technological assumptions of the UAS, including the aircraft type, which was defined as being similar to an ATR-42, DHC-6 Twin Otter, DHC-8, Cessna 208, Beechcraft 1900, or King Air. It was also explained that the UA were equipped with standard current day technology in addition to expected future technologies, including supplementary vision systems (e.g., on board cameras), an advanced collision avoidance system (e.g., Resolution Advisory [RA] and Detect and Avoid [DAA]), and that Satellite Communication [SATCOM], and/or terrestrial C2 links were available for the full flight.

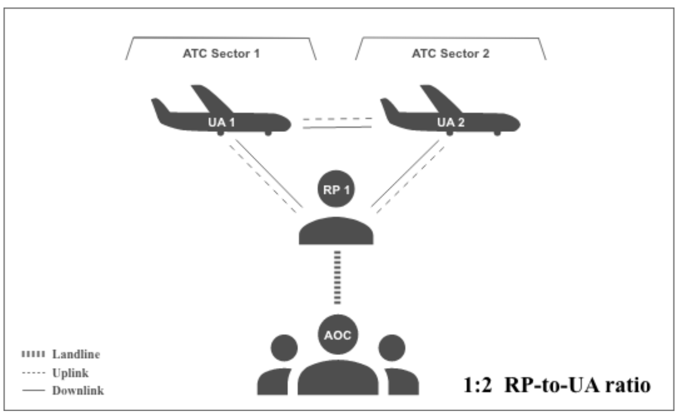

Fig. 2. Simplified illustration of a 1:2 RP-to-UA m:N ratio.

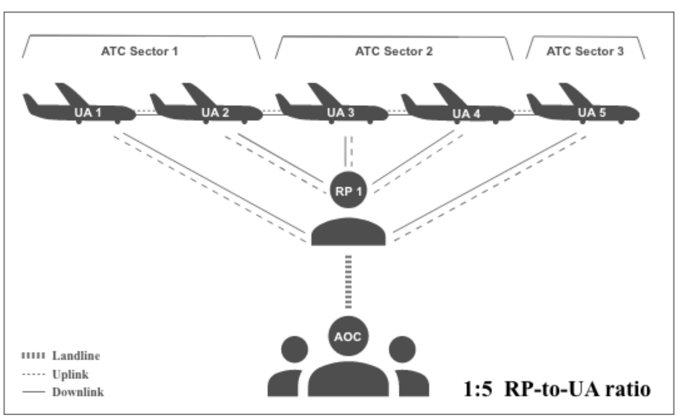

Fig. 3. Simplified illustration of a 1:5 RP-to-UA m:N ratio.

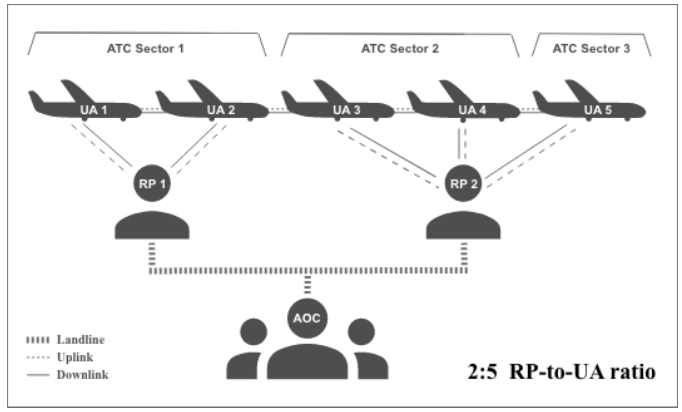

Fig. 4. Simplified illustration of a 2:5 RP-to-UA m:N ratio.

D. Materials

To facilitate discussions, 25 hypothetical scenarios were generated by researchers using data from the previous tabletops and six operational challenge categories highlighted as potential problem areas for large UAS integration (Table 1). All scenarios involved a single operator in control of multiple vehicles but varied in terms of specific phase of flight, airspace class, as well as nominal and non-nominal situations (e.g., LC2L, weather avoidance, and traffic delays). These hypothetical scenarios, grouped by class and/or phase, included Class B or E enroute, Class B or C regional TRACON approach, Class D or E non-towered approach including Common Traffic Advisory Facility (CTAF) environments, and Class B or C towered preflight, surface and departure operations. Although only two scenarios were designed to focus on the RP handoff challenge (scenarios E3 and E4), this topic was consistently raised in nearly all scenario discussions. To help visualize these scenarios and guide discussions, animated graphics were displayed to participants as the moderator read scripts of the scenarios aloud. A list of both general and scenario-specific questions were pre-constructed to act as prompts for discussions about barriers to integration as well as proposed solutions to those barriers. Workload and situation awareness impacts on ATCs, RPs and dispatchers arising from the issues and mitigations discussed were key focus areas within the prepared prompts.

A sample scenario involved three UA en route to three different destinations in the same geographical area (Fig. 5). The first UA was on the first point of the standard terminal arrival (STAR) to a destination Class B airport, the second UA was 50 NM from a small municipal Class E airport, and the third UA was departing a Class B airport and on a direct route to the first waypoint. One of the UA encountered a developing weather cell and anticipated a weather avoidance maneuver. The RP executed a contingency plan while monitoring all other UA under their control. If the workload associated with this weather avoidance maneuver and communicating the contingency plan with ATC for approval exceeded personal thresholds, the pilot would decide one of two things: to keep the non-nominal UA and handoff one or more of their nominal operations, or handoff the non-nominal aircraft to another RP.

TABLE I. TABLETOP SCENARIOS

Phase of flight	*Scenario Number*	*Scenario Name*
En route	E1	Weather Avoidance
	E1a	LC2L[a] During Weather Avoidance
	E2	DAA Alerting and Guidance
	E3	Mid-Flight UA Handoff
	E4	GCS Position Relief
	E5	Managing Multiple ATC Frequencies
	E6	Data Link Management
Approach	A1	Metering
	A1a	LC2L Descent to Landing
	A2	Holding
	A2a	LC2L While Holding
	A3	Sequencing
	A4	TRACON Resequencing
	A5	Missed Approach and Diversion
	A6	DAA Alerting and Guidance
	A7	Class D Pattern Entry
	A7a	LC2L Class D Pattern Entry
	A8	CTAF Operations
	A8a	LC2L CTAF Operations
Surface	S1	Hold Short with Tower
	S2	Taxi Instructions & Following Traffic
	S3	LC2L During Taxi
Preflight	P1	Preflight
Departure	D1	Position and Wait & GDP[b]
	D2	Rejected Takeoff

[a] Loss of command and control (C2) link (LC2L).

[b] Ground Delay Program (GDP).

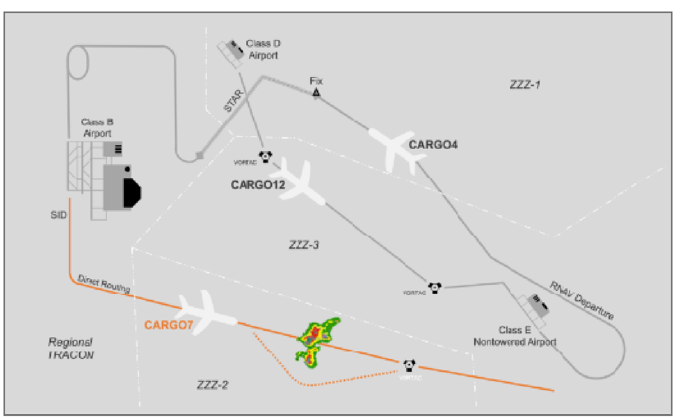

Fig. 5. Example scenario graphic that depicts 3 uncrewed aircraft (UA) being controlled by 1 remote pilot (RP) in terminal areas.

III. RESULTS

The procedural and technological solutions for handoffs in an m:N configuration were iteratively captured throughout data collection as they were envisioned by SME participants. It was stressed at the start of data collection that the participants' primary overarching goal was that the safety, efficiency, and predictability of operations be maintained in all contexts when m:N is applied. Arriving at a consensus for the optimal combinations of tools, technologies, best practices, and procedures was susceptible to stalling due to the initial ambiguous definition of the m:N architecture. However, though the methodology applied in this study, participants were able to jointly design their preferred architecture and more firmly agree upon specific solutions to many challenges, of which handoffs are highlighted here. Although the question for when the legal responsibility should transition during handoffs was raised, no consensus was able to be reached during this tabletop and is not included in these results. Due to this, "RP" in this paper only assumes that the remote pilot has *physical* control of the UA and makes no assumption about the best practices for the transfer of legal responsibility.

A. Who receievs a handoff

Before determining which RP would be best suited to accept a handoff due to nominal or non-nominal events, it was important for participants to first define how their hypothetical facility was structured (Fig. 6). By the end of the three sessions, the pilot, controller, and dispatcher participants drew upon their distinct experience in their respective facilities to notionally design an example "Command Center" for large UAS operations but emphasized that individual companies would ultimately be responsible for the arrangement of their own facilities. However, this exercise to create a common picture assisted participants when holding discussions in order to agreement more easily on potential solutions.

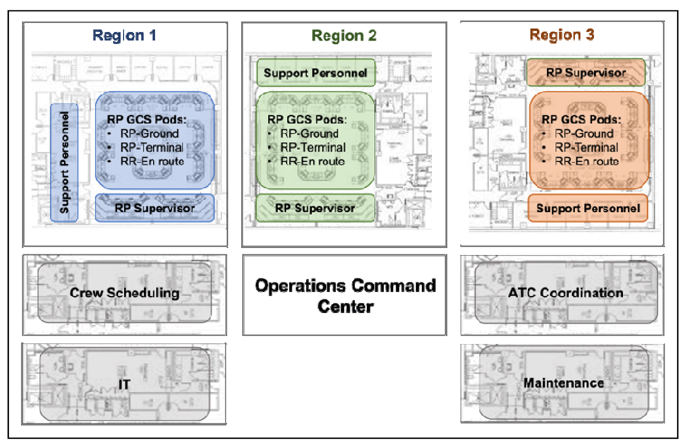

Fig. 6. Example remote pilot (RP) facility or Operations Command Center notionally designed by participants during the study.

Participants concurred throughout scenario discussions that an RP who is accepting a handoff have good understanding of the UA's current status and airspace, in addition to having the capacity to accept additional workload. The physical positioning of RPs was discussed at length and the concept of strategically co-locating pilots within "pods" was highly desired to improve situation awareness. They imagined that these pods would be defined by geographical region and may even be representative of each phase of flight for a set of operations. Such an arrangement was thought to naturally facilitate familiarity with the airspace, including the current flow, traffic, and weather.

For nominal planned handoffs at prescribed transition points, such a personnel configuration would allow incoming pilots to passively observe their next UA "over-the-shoulder" to build situation awareness before taking positive control. Overlapping responsibility whereby the oncoming RP observes the flight for a period of time before taking control, and the outgoing RP observes for a period of time after the handoff, was also proposed but not widely agreed upon as it may limit the upper bounds of the m:N ratio.

For non-nominal unplanned handoffs due to unforeseen high workload conditions, participants thought that the co-location of RPs would still be advantageous, but also detailed a method for selecting an oncoming RP and streamlining situation awareness acquisition. RP selection could be assisted by employing a continuous workload assessment tool, either calculated automatically by considering current UA and airspace conditions, or through manual entry by the RPs. In the event that an RP indicated that they need to hand off a UA, a system could identify other RPs within an acceptable workload threshold and, combined with their current phase and area of operations, automatically determine a list of best candidates to receive that UA. In this thought experiment, participants also mentioned that it could be helpful for an RP to indicate their own personal workload limits in this system and that, if selected to receive a handoff, they should have the ability to review the flight deciding to accept control.

New or amended roles and their potential contributions to the unplanned handoff challenge were also proposed. Participants cited that dispatchers could help predict future increases in workload due to factors like traffic, weather, and runway changes or closures and disseminate that information to RPs so they might choose to hand off some of their UA before a workload threshold is reached. Similarly, if an RP's UA was following another from the same company, the pilot of the forward aircraft might also be able to provide workload information or even strategies to prevent overload for the following RP. Having a supervisor or dedicated standby RPs accept non-nominal handoffs was also put forward as a solution but was not well supported as it was not conducive to the goal of scalable m:N operations and efficient use of the human resource.

B. What UA to handoff

In the case of unplanned handoffs, pilots were initially largely consistent in their preference to retain control of the non-nominal aircraft and handoff the nominal UA. The reasoning behind this choice pointed to the need for fast situation awareness transfer during unplanned handoffs that may lack the luxury of time that is present for planned handoffs. Specifically, building an accurate picture for a non-nominal flight would likely take more time to achieve, therefore this decision was rooted in the concern for safety during a potentially hazardous or high workload time.

While keeping a non-nominal UA and load-shedding a nominal one to remain within a workload threshold was preferred in most scenarios discussed, an exception for which vehicle to keep or pass began when considering airspace class. The argument offered was that when the vehicle is transiting a more complex airspace, it may take more time to transfer awareness to another RP. For example, the task load and task pace are frequently higher in a Class B approach environment, so even if the UA is in a nominal state, it may be safer to keep that nominal UA and handoff a non-nominal vehicle in a less time-constrained en route environment. Therefore, an RP may make the decision for which UA to hand off in an unplanned situation based not only on non-nominal events, but also on the amount of interaction the airspace requires of each operation.

Task sharing was proposed by participants as an alternative to a full UA handoff caused by extra workload associated with non-nominal events. This topic was too broad to cover in depth during the current study; however, it should be noted that current day practices within remote aircraft operations and crewed flights may present a different set of solutions where some of the more high attention tasks could be temporarily assumed by another RP or supporting role to allow the original RP to retain their aircraft until their workload returns to an acceptable level.

C. Where or when to handoff

Beyond agreement that planned handoffs should occur at transition points between phases of flight, ATC and pilot groups proposed best practices to help build predictability in operations and facilitate undisturbed ATC communications. Modeled after current day controller practices for crewed aircraft, participants suggested that handoff locations be in low workload areas such as near sector boundaries, but before initial radio contact with the next sector. Controllers confirmed that when they currently transfer flights to a new frequency, they do so after they are confident that there will not be any immediately necessary instructions, giving the next controller time to review the flight, and consequently, also giving the handoff RP pair time to complete the UA transfer.

D. How to faciliate a handoff

Automation has the potential to play a large role in streamlining the handoff process. In addition to the previously discussed method to assess RP workload and determine handoff RP candidates, automation was thought by participants to be consequential for pre-populating checklists for both planned and unplanned handoffs. A brief discussion of notional handoff checklist items included parameters such as the UA position, altitude, airspeed, previous and expected clearances, flight anomalies, nearby traffic, and specific information about the cargo onboard, if deemed necessary. If such automation is implemented, pilots cautioned that it would still be important for the RP to verify all checklist items, but that the workload would likely be lower than if they had to input that information themselves. In general, pilots thought that many low-level piloting tasks could be good candidates for automation, but always in conjunction with notification to the RP, if not verification and acknowledgment.

As previously mentioned, there were additional supportive roles imagined when discussing a notional command center or facility design beyond the initiating and receiving handoff RPs. These additional roles were regarded as agents to enable a scalable m:N ratio. Specifically, a design which promotes a common operating picture for all entities invested in a flight could enable those stationed in new or expanded roles (e.g., dispatchers, area supervisors, or dedicated communications staff) to more easily lend temporary support to the RPs experiencing a higher level of workload. Participants imagined working within an open communal space where large screens would display information about all or a group of flights in addition to the individual, tailored screens at their GCS.

Good interface design at the GCS itself was always assumed when imagining the greatest scalability for m:N while maintaining safety. Participants suggested different techniques to reduce the frequency of interaction or button presses by simplifying the number of screens and linking between different systems, for example, highlighting the corresponding radio frequency on the communication interface for a UA if the RP has adjusted, but not yet executed, a heading change. To improve situation awareness and response time, highlighting aircraft that require immediate attention, perhaps paired with an audible alert, was a widely accepted best practice. Particularly for the handoff challenge, either a formal or informal procedure for RPs to keep running notes on significant events throughout a flight was proposed as another way to pass pertinent high-level information to an RP accepting a UA handoff.

IV. Conclusion

The results from this tabletop support m:N as being a viable path towards fully autonomous control, specifically when viewing through the lens of the handoff challenge. With proper procedures, technologies and support via automation and/or other personnel, pilot participants felt that some high workload handoff-related remote pilot tasks could be mitigated to remain within a reasonable workload threshold while maintaining adequate situation awareness. Discussions revealed many technological and procedural solutions to overcoming the added workload of controlling multiple vehicles, but also revealed situations where a workload tipping point could be reached, necessitating a need to shed some of the pilot workload load to maintain a sufficient level of safety. Researchers probed participants on different scenarios for insight into who should receive those handoffs, what set of tasks (or an entire flight) should be handed off, and how that handoff should be facilitated by procedures and technology. The resulting feedback offers initial guidelines to support efficient and safe transfer of control while attempting to maximize the m:N ratio.

Although additional challenges such as managing multiple frequencies and specific contingency situations still need to be addressed while scaling up from 1:1 operations, the hurdle of handoffs is one that spans most flight scenarios and should have agreed-upon mitigations before these flights progress to m:N. Suggestions for future technologies and procedures were envisioned by participants, but many of the handoff solutions presented in this paper may be made possible by implementing current day technologies and best practices already used in similar fields with continuous operations. This paper presents a selection of means to mediate remote pilot workload and assist the positive transfer of situation awareness in load-shedding flight activities prompted nominally and non-nominally. Many of the barriers associated with integrating m:N-operated large UAS into the NAS are intertwined, with the severity of each being partially defined by the expected workload associated with others. Leveraging the results of this tabletop study to understand and hold constant the challenge and solutions for handoffs could serve to concentrate future research on other m:N challenges for large UAS operations and their associated technological and procedural solutions.

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