Identifying Human Factors Research for Unmanned Aircraft Systems and Advanced Air Mobility

William N. Kaliardos
Office of NextGen
Federal Aviation Administration
Washington DC, USA
bill.kaliardos@faa.gov

Jon Holbrook
National Aeronautics and Space Administration
Hampton, VA, USA
jon.holbrook@nasa.gov

Alan Hobbs
San Jose State University Research Foundation
Moffett Field, CA, USA
alan.hobbs@nasa.gov

***Abstract*—This paper identifies some of the key human factors (HF) challenges when integrating Unmanned Aircraft Systems (UAS) and Advanced Air Mobility (AAM) into the civil airspace. Unique HF considerations—those which are derived from the key differentiating aspects of UAS/AAM compared to conventional aviation—are the primary basis for identifying HF research opportunities. By identifying what makes UAS and AAM fundamentally different from conventional aviation, from a human integration perspective, HF research can be targeted to effectively inform best practices, standards, policy, guidance, and regulations associated with aircraft and air traffic systems and operations.**

HF research areas are discussed within the following topic areas: Sustained low-altitude operations; loss of natural sensing; novel aircraft; novel operations; link management and lost link; link performance; distributed pilot teams; and increased automation. The identified research descriptions are intended to serve as illustrative examples of what research is fundamental, and why. They are not intended to prescribe, prioritize or exclude research.

Keywords—human factors, advanced air mobility, AAM, unmanned aircraft systems, UAS, drone, remotely piloted aircraft systems, RPAS, human-system integration, HSI, automation, autonomy.

I. INTRODUCTION

Unmanned Aircraft Systems (UAS) and Advanced Air Mobility (AAM) are expected to be transformative concepts within the world's civil airspace, including for cargo and passenger-carrying operations. Both bring unique design and operational considerations, yet must be accommodated by current frameworks and processes that are dominated by conventional aviation participants.

Rapid advances in technology create opportunities for novel operations that have the potential to transform the roles of humans and human-automation interactions. It is particularly critical that new operational designs and concepts adequately consider how those changes in technology will impact and interact with the humans in the system. To support that consideration, the state of knowledge within the human factors (HF) discipline must keep up with the pace of technological developments.

This paper identifies an approach to thinking about HF research needed to support integration of UAS and AAM into the civil airspace. For UAS/AAM, many HF considerations are well known and readily addressed based on extensive existing knowledge, standards, and requirements from conventional aviation. However, there are also unique HF considerations for UAS/AAM that present challenges. Separating these unique HF considerations—those which are derived from the key differentiating aspects of UAS/AAM compared to conventional aviation—is particularly important for identifying gaps in knowledge, standards, and requirements, which in turn imply opportunities for HF research.

HF research needs are discussed primarily within the context of pilot and air traffic operator roles, however, the approach equally applies to ground personnel, maintenance, dispatch, and other operational personnel. This paper is not intended to be comprehensive or prescriptive, but to describe an approach to thinking about human factors research needs supported by examples.

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A. *UAS and AAM Descriptions*

The term "Unmanned Aircraft System" (UAS) refers to an aircraft that operates without an onboard pilot, along with the equipment (e.g., control station, radio link) necessary for the safe and efficient operation of that aircraft.

The emerging concept of Advanced Air Mobility (AAM) envisions new methods of moving people and/or property by air using advanced technologies such as distributed propulsion, electric powered aircraft, and increasingly autonomous technologies. Some AAM concepts do not require an onboard pilot, whereas in other cases the advanced aircraft is operated by an on-board pilot.

This paper makes comparisons between UAS/AAM, and "conventional" aircraft and operations. "Conventional" is intended to mean the majority of aircraft currently operating in the civil airspace that are not UAS or AAM.

B. *Human Factors*

Human Factors is concerned with the application of what we know about people, their abilities, characteristics, and limitations to the design of equipment they use, environments in which they function, and jobs they perform. The intersections of various aspects of human, team, and organization characteristics across the range of equipment, environments, and roles in UAS/AAM encompasses a very large research space.

Human performance is tightly coupled to nearly all system elements across all stages of the system life-cycle. Systems that are intended to support, replace, or change human tasks should be designed with an awareness of the tasks that humans perform, and how they perform them.

Human performance in aviation systems is frequently examined with an emphasis on human failures and less attention paid to the full range of human contributions to system performance. As a result, the data that are available on human performance are systematically biased toward "humans as problems", which can perpetuate a pattern of overestimation of technology capabilities and underestimation of human capabilities. Although technology and humans each bring capabilities and limitations to system performance, issues related to the interactions between technology and humans have not always been appropriately. considered in visions/concepts of future operations.

As UAS operations become more common in the airspace system, and as AAM concepts and business models continue to develop, there is a need for a better understanding of the HF considerations associated with these operations.

C. *Existing HF Guidance*

It is important to recognize that a large body of knowledge about HF has been accumulated from conventional aviation development and operational experience. This has resulted in a considerable body of HF standards, guidance, requirements, policy, regulations, and research products for conventional aircraft and air traffic control (ATC), with applicability for development as well as regulatory approval. For simplicity, such material will be referred to in this paper as "guidance" unless noted.

Much of the existing HF guidance is still relevant to the emerging sectors of UAS and AAM. In fact, analysis of UAS accidents/incidents identify a significant proportion of causal factors that are indeed HF related, but in many cases, the events might have been avoided if manned aircraft HF guidance had been followed [1,2].

For instance, UAS/AAM operator displays still should be designed to ensure that information is clear and unambiguous. Hence, general HF principles and guidance related to information needs, ergonomics, use of text, symbols, numbers, colors, labels, etc., remain largely relevant. A Federal Aviation Administration (FAA) Advisory Circular (AC) [3] refers to HF guidance and topic areas such as:

- Display Hardware
- Electronic Display Information Elements and Features
- Considerations for Alerting
- Organizing Electronic Display Information Elements
- Controls
- Design Philosophy
- Intended Function
- Error Management, Prevention, Detection, and Recovery
- Workload
- Automation

The AC references additional reports and other HF resources, and also states, "many of the same human factors considerations are applicable to UAS control stations and as such these documents may serve as a starting point for the design and evaluation of UAS control stations." The same rationale applies beyond pilot-interface design considerations, and extends to aircraft operations, as addressed in Title 14 of the Code of Federal Regulations (14 CFR) Parts 91, 121, and 135, and other areas in which HF guidance exists for conventional aircraft.

For air traffic management, similar HF topic areas are addressed. A primary example is the FAA HF Design Standard [4], which is applied to FAA acquisitions, typically as design requirements. Such existing guidance has evolved within the paradigm of conventional aircraft and operations, and although this guidance material may not specifically address UAS and AAM, much of it is likely applicable.

Lastly, existing HF guidance is often not labeled as "human factors". However, aviation resources such as those listed above, and others [5], can be helpful in identifying guidance that is relevant to HF.

D. *Criteria for Identifying UAS/AAM HF Gaps*

UAS and AAM introduce HF considerations that have not previously been major areas of concern in conventional aviation. These new considerations must be identified as knowledge gaps in order to develop guidance, which ideally is informed by HF research. For example, the report from the National Research Council's Committee on Autonomy Research for Civil Aviation [6] states, "incorporating increasingly autonomous systems and aircraft in the NAS (National Airspace System) would require humans and machines to work together in new and different ways that have not yet been identified."

The key challenge is to understand the gaps in current HF guidance. In this paper, three driving criteria were used for determining new HF research needs for UAS and AAM:

1. Derived from key characteristics.

   The scope of considerations can be derived, directly or indirectly, from the core definitions or defining characteristics of UAS and AAM.

2. Existing guidance is insufficient

   Existing guidance is or might be insufficient, because it is incomplete, inappropriate, or not applicable.

3. Research is insufficient

   Research and analysis has not yet been performed and documented sufficiently to inform UAS and AAM guidance.

The development of Minimum Operational Performance Standards (MOPS) for UAS Detect and Avoid (DAA) systems [7] is an example of HF research helping to fill in gaps in existing guidance. The MOPS leveraged aircraft symbology guidance from a previous standard for conventional aircraft systems with traffic displays [8]. However, there was a need for additional modeling and human-in-the-loop simulation to define "well clear" alerting thresholds, and suggestive guidance for maneuvers. HF research efforts were needed because existing guidance for traffic avoidance did not address the unique challenges of remote piloting or the lack of a quantitative definition of "well clear" [9].

Eventually, HF research needs become more apparent as specific guidance is developed. However, estimating HF research needs is proposed here for strategic planning purposes. The following section identifies UAS/AAM HF research opportunities based on the above criteria.

II. EXAMPLE HF RESEARCH NEEDS FOR UAS AND AAM

This section describes the following research topics areas for UAS and/or AAM: Sustained low-altitude operations (response times, traffic/terrain avoidance, microweather); loss of natural sensing; novel aircraft; novel operations; link management and lost link; link performance (control link performance, relay of voice communications); distributed pilot teams (control handoffs, multi-aircraft control); and increased automation.

A. Sustained low altitude ops

Many AAM and UAS aircraft fly at low altitudes during a substantial part of their normal operations, versus just the takeoff and landing phases. Examples include those operating within Unmanned Aircraft System Traffic Management (UTM) and Provider of Services to UTM (PSU) traffic management system volumes, as well as other operations made practical by UAS, such as visual surveillance and inspection. Sustained low altitude operations increase operational complexity for various reasons, due to decreased buffers and allowable pilot reaction times, traffic density and detection, ground/obstacle proximity, and localized "microweather" effects.

1) Response times

Operations at low altitudes can restrict time to respond in unplanned situations, and operations over populated areas can affect alternate landing decisions (e.g., potentially increase the number of prepared landing sites, but decrease the number of unprepared landing sites relative to operations over rural areas). While often associated with emergency situations, even "routine" operations can be characterized by unpredictability and ambiguity, requiring that decisions be made under uncertainty and/or time pressure. Information about traffic, terrain, obstacles, weather, vehicle state, and operator state may be distributed across various systems and agents, and that information must be appropriately integrated by the decision maker. New systems and procedures may be needed to address these concerns, including the human integration aspects.

2) Traffic and terrain avoidance

A primary safety concern is the ability to avoid other aircraft and terrain in complex low altitude operations. Human roles and tasks differ, depending on whether pilots are onboard or remote, yet humans remain responsible for safety. Other dependencies include future cooperative environments such as the Extensible Traffic Management (xTM), which complements the conventional provision of Air Traffic Services (ATS) for future passenger or cargo-carrying operations/flights, and UTM [10].

HF challenges associated with traffic and terrain avoidance are exacerbated by sustained low altitude operations. Pilots have less time to react, but also may interact with highly diverse traffic, both in terms of aircraft (manned/unmanned, small/large, surveillance sources, etc.), operations (vertical/horizontal flight, corridors, vertiports and other terminals), maneuvering constraints imposed by terrain/obstacles and other property, and by microweather. Some surveillance such as active radar at low altitudes is especially prone to false tracks, which must then be interpreted by automated systems or humans for verification. As a result, traffic detection and estimation of well clear, and avoidance decisions are likely to be more challenging than with conventional operations.

Human operators may also face challenges regarding the interoperability of the various traffic/terrain avionics and their associated procedures. Systems that have been developed or are currently in development include TAS [11], TCAS I [12], TCAS II [13] ACAS-Xa/Xo [14], ACAS-Xu [15], ACAS-sXu [16], ACAS-Xr [17], DAA [18], TAWS [19], H-TAWS [20], as well as Airborne Surveillance Applications that utilize Automatic Dependent Surveillance Systems [21]. Each of these systems address interoperability and human factors within their scope of operations, but it is unclear if human operators will be adversely affected by the potential operational complexity from varied behaviors across these systems. Examples include understanding and predicting traffic alerting logic and horizontal/vertical maneuver guidance. HF research may therefore need to address system-of-systems integration related to the variety of traffic/terrain avionics systems.

3) Microweather

UAS/AAM aircraft operating at low altitudes and in urban areas will be subject to "conventional" weather phenomena (e.g., wind gusts, thunderstorms, icing, hail, lightning, low visibility, etc.) as well as "microweather" phenomena associated with topographic features and human-made structures. Many UAS/AAM aircraft are small or have design features that are susceptible to microweather effects.

Microweather information is critical for sustained operations at low altitude. Relative to conventional aircraft weather information and microweather information is fine-grained and localized, and will likely result in significantly greater volumes of weather data, with high spatial and temporal frequencies. Furthermore, microweather data are likely to be characterized by a greater degree of uncertainty and inconsistency when compared to current weather products. The quality and uncertainty of the data will also limit automated capabilities, and such system limitations will need to be understood by the operators and taken into account.

While research has been conducted to understand microweather effects and potential information infrastructures [22], little has been done to examine the human use of microweather in decision-making.

B. Loss of natural sensing

Conventional aircraft pilots gain information about their aircraft and environment not only through artificial means such as cockpit displays and controls, but also more directly through their natural senses. This includes what pilots see out the window, and what they see, hear, smell, and sense somatically within the cockpit and cabin. This is a well known difference between manned and unmanned aircraft [23,24] yet it remains unclear how pilot tasks and safety are affected, and what, if any, mitigations are needed through new designs or operations.

Example regulations related to natural vision include 14 CFR 25.773 [25], which requires pilot compartments to provide an extensive and clear view to perform any maneuvers, and 14 CFR 91.175 [26], which requires that visual references like runways and approach lights are distinctly visible and identifiable. Pilot operational tasks involving natural vision are ubiquitous and complex, yet are not characterized sufficiently to understand what is needed for remote operation or onboard automated vision.

Other non-visual natural sensing has also been assumed within conventional aviation, even if the sensing has not been explicitly addressed in regulations. For example, background noise can be important for detecting anomalies and failures, such as the sounds from an engine during a flameout. Forces and vibrations from aircraft systems or aerodynamics provide naturally salient information to vestibular, haptic, and proprioceptive senses to detect turbulence, aircraft attitude, accelerations, and other states that are critical to the safety of flight. This type of sensing remains important even when visual information is unavailable, as in Instrument Meteorological Conditions (IMC). The full range of non-visual natural sensing in the cockpit has not been characterized in detail, perhaps because of assumptions that pilots could always make use of this rich, omnidirectional set of natural sensing onboard the aircraft without risk of overloading visual channels with displays.

C. Novel aircraft

UAS and AAM aircraft designs are often novel due to their defining characteristics (e.g., no onboard pilot) or design choices (e.g., electric propulsion). This section discusses novelty from the human operator perspective, relative to conventional aircraft.

An example of unmanned aircraft design novelty, from a human integration perspective, is the potential decrease in manual control compared to conventional aircraft. Basic stick-and-rudder skills have always been the foundation of piloting, because direct manual control has either been the only means of control, or at least an optional mode for automated aircraft. However, unmanned aircraft preclude manual levels of control of some states not only as a design choice, but also because of control link performance that necessitates onboard automated control (e.g., inner loop control). For example, a remote pilot might not be able to manually control attitude like bank angle, but instead might issue supervisory control commands to an autopilot. The novelty is not high-level human control; the novelty is the aircraft not allowing low-level (manual) control. What states, then, need to be displayed to the human operator, when the aircraft is not directly controllable by the human?

With the absence of a cockpit and onboard human pilots, unmanned aircraft can be much smaller than conventional aircraft. This directly affects the ability to carry onboard equipment, some of which supports human roles, such as information available at the control station (e.g., from onboard weather radar), and information available to other aircraft and air traffic facilities. The consequences of equipment limitation remain to be determined as UAS categories and their associated design and operational requirements evolve.

Clearly, the small size of some unmanned aircraft can make them more difficult to detect. Conventional aircraft are limited to a practical lower bound in size and cross section, and human operators have expectations from experience and training for detection tasks and other tasks involving estimation of distance, altitude, etc. For example, pilots are required to see and avoid other aircraft visually [27], and tower controllers rely on visual tasks to safely separate aircraft in the airport vicinity, whether in the air or on the ground [28,29]. Air traffic controllers may also conduct visual operations in IFR, requesting pilots of trailing aircraft to visually identify and follow leading aircraft on approach to the runway. All these visual tasks might be adversely affected by the smaller size of unmanned aircraft, which reduces the subtended visual angle at the observer. Active surveillance radar information based on reflected energy can also be adversely affected. However, compensatory methods to increase detection through enhanced conspicuity are challenging [30], and more research is needed to understand small aircraft effects on visual task performance, safety risks, and mitigations.

AAM aircraft are characterized by novelty in their fuel source, propulsion systems, and automated systems, to name a few features. For example, many AAM aircraft are electric vertical takeoff and landing (eVTOL). eVTOL batteries drain at highly variable rates depending on phase of flight and environmental conditions. Being able to monitor and, more importantly, predict battery performance is critical for strategic mission planning as well as tactical decision making such as the need to unexpectedly hover in a hold pattern, which consumes power at high rates. How to represent predicted states and uncertainties around those predictions to best support human decision makers needs to be explored.

eVTOLs are complex aircraft and may need new uses of automation or new controls and displays to support pilot control tasks [31]. For example, transitions between vertical and forward flight will involve significant vehicle configuration changes, and distributed propulsion systems such as multiple rotors may require new information to be displayed, and new methods of flight control, which must be designed and evaluated for alignment with human capabilities. This includes non-normal events such as engine failure, in which pilots need to rapidly assess the event and override automation if necessary. Such tasks can be especially challenging for humans to manage with complex AAM aircraft at low altitudes in dense environments.

D. *Novel operations*

Novel AAM and UAS aircraft enable novel operations, and some aspects of these operations have impacts to humans managing aircraft or air traffic systems.

Aircraft and operations are expected to be highly diverse, such as in aircraft performance (e.g., speed, climb/descent rates, turn rate), size, equipage (e.g., surveillance, transponders), control station locations, termination points, sensors, automation, and operations (e.g., infrastructure inspection, urban small cargo deliveries). This diversity will add a new form of operational complexity for aircraft operators and air traffic service providers. Key questions arise regarding the information that will need to be exchanged between aircraft and the various traffic management services that may be involved.

UAS also provide some illustrative examples of novel operations that are not practical with manned aircraft. Ditching an unmanned aircraft on land may be an option when there are no passengers, and when controlled flight and terminal landings are not possible and continued flight may jeopardize safety of other airspace users or people/property on the ground. In such cases, what systems, procedures, and information can help support decisions for safe ditching? Another example is swarm control. Unmanned aircraft can be smaller than conventional piloted aircraft, and with automation many aircraft can be internally coordinated while being externally controlled as one entity. What information and degree of control/communications is needed at the individual aircraft level and at the group level, especially when considering degradation of individual aircraft? Shielded operations is another example of novel UAS operations. This refers to operations close to structures (e.g., buildings, bridges), which leverage other traffic avoidance of these structures to mitigate UAS DAA risk. This concept is currently being explored, and questions remain about what distances from structures is allowable for shielded operations, how operators will understand these spatial constraints, and how shielded operations will integrate with non-shielded operations.

Many AAM operations will be characterized by frequent, short-duration flights with increased operational tempo [10], resulting in a higher proportion of time being spent in highly dynamic phases of flight with limited “down time”. Similarly, limited time on the ground between flights could restrict time available for flight safety and aircraft maintenance checks. The effects of sustaining a rapid operational tempo over time on personnel fatigue and readiness to perform, need further exploration. While it is one thing to show that a human or multi-agent team can perform at a given operational pace, it is also critical to explore pacing parameters that affect the operators’ abilities to sustain such operations over an extended time. Because such studies are typically more difficult, expensive, and (of course) time consuming to perform, there is far less research available about sustained operations, despite a critical need for such studies.

E. *Link management and lost link*

A wireless data link for aircraft control is unique to unmanned aircraft and therefore not addressed in today’s manned aircraft regulations and standards. Because the data link is critical for safe operation, yet is subject to degradation and failure modes very different from control links in manned aircraft (e.g., cables, fly-by-wire), link management and monitoring is an essential aspect of UAS operations. Therefore, in addition to standard pilot tasks of flightpath management, and configuration of onboard systems, the crew responsible for a UAS is faced with a new set of tasks associated with the management of the control link [32]. These tasks include planning the link modalities (e.g., terrestrial/satellite, frequencies) that will be used during the flight, monitoring the performance of the link during flight, anticipating conditions that may cause link interruptions (e.g., coverage area, aircraft position and orientation), switching link pathways, and responding to link degradations. The link is often managed by specialist personnel, however the pilot or operator still needs to be aware of link status [33]. If the link utilizes line-of-sight radio communications between the aircraft and a terrestrial antenna, intervening buildings or terrain can obstruct radio signals, or produce interference via multipath propagation. When the radio link is via satellite, additional factors come into play, including increased latency and the likelihood that communications will be routed via ground infrastructure between the pilot's location and the satellite ground station. Regardless of whether communication is via satellite or terrestrial radio systems, the crew must remain aware of the link coverage area, and be able to predict the locations in 3D space where the aircraft may experience degraded or lost communications. Certain aircraft maneuvers may also interfere with the control link if on-board antennas are moved out of alignment or blocked by aircraft structures during the maneuver

Human actions are among the most common reasons for link problems in UAS [34]. Potential human causes of lost link include flying beyond the range of the ground station, flying into an area where the signal is masked by terrain, frequency selection errors, abrupt aircraft maneuvers, and physical disruptions to equipment. In addition, the pilot must be alert to radio frequency interference, whether from malicious or unintentional sources.

An important consideration for aircraft operators and ATC is determining how to deal with link interruptions. Research and guidance to date indicate that human factors considerations are critical [35,36,37]. The unmanned aircraft response will involve transmitting a predetermined surveillance code, and may also involve, after a further delay, the aircraft activating a pre-programmed maneuver, such as flying to a predetermined location, or landing automatically at a preselected landing area. Although the aircraft response needs to be operationally suitable, the important factor is that that ATC knows what the planned response will be, in order to take the necessary steps (e.g., clear the airspace).

Some link outages will last a few milliseconds, whereas others may extend for minutes or even hours. It would be disruptive to ATC and aircraft operators if the aircraft responded to each brief interruption. An important aspect of link management is to ensure that the unmanned aircraft is programmed to respond to link interruptions only when a pre-determined time has elapsed since the link was lost. Durations of this elapsed time can depend on a number of variables, which need to take into account human factors such as operational suitability, distractions, and workload. For example, in some locations, particularly at low altitude, it may be appropriate for the unmanned aircraft to execute a pre-programmed maneuver after only a brief link interruption. Elsewhere, the aircraft may be able to safely continue along its planned flightpath for an extended period before activating a pre-programmed maneuver. As with alerts, if lost link declarations are too sensitive, they are a nuisance and can lead to operator desensitization, and if not sensitive enough they reduce the available time for operators to mitigate the safety risks.

F. Link performance

1) Control link performance

The performance of a radio control link can be described in terms of availability, continuity, integrity, and latency [38]. Some level of link degradation such as drop outs (lack of availability), data errors (integrity) and latency are to be expected with any radio communication system. The aim of designers must be to reduce the likelihood of such degradations below a target level, thereby providing the required link performance (RLP) for the particular operation. The RLP is likely to vary depending on factors such as the level of automation on board the aircraft, whether humans are in direct control or at higher levels of supervisory control, the flight environment, air traffic control requirements, properties of the equipment at either end of the link, and other risk considerations.

2) The relay of voice communications

Despite advances in technology, aviation still relies heavily on radio for voice communications. In current aviation operations, transmissions of air traffic controller speech may be affected by small latencies due to communications processing on the ground, however the pilots of conventional aircraft can hear voice transmissions from nearby aircraft in near-real time (despite imperceptible delays introduced by on-board very high frequency [VHF] radio systems). UAS pilots can benefit from the situational awareness that comes from participation in the party line VHF communications of pilots and ATC, but this may come at the cost of noticeable delays if voice communications between the UAS pilot and other airspace users/ATC are transmitted and received by radios located on the UAS or in the vicinity of UAS operations. Voice latencies can increase the likelihood of hazardous step-ons, in which two people attempt to transmit simultaneously. Voice latencies are likely to be most problematic when a satellite link is involved, as illustrated by the following report from the pilot of a UAS:

> "There is a delay between clicking the press-to-talk and talking. This is very difficult to manage when in very busy airspace, and listening for a gap to talk. Sometimes by the time we press the talk button, with the satellite delay, the gap is gone, and we step on other aircraft" [34].

Telecommunications research has found that latencies longer than 250 milliseconds can significantly disrupt phone conversations [39]. Consistent with this finding, FAA policy requires that communications systems deliver an average one-way delay between pilot and ATC voice communications of less than 250 milliseconds [40]. Several studies have examined the impact of voice latency on ATC communications (e.g., [41,42]). However, to date, there has been little, if any, research on the impact of voice latency on pilot-pilot communication.

G. Distributed pilot teams

Remote operation provides both opportunities and challenges related to flight crews, who are no longer constrained by physical aspects of the aircraft cockpit. One of these is distributed teams, such as pilots in multiple locations, and/or larger numbers of operators with varied or dynamic roles.

1) Remote control handoffs

A longstanding concern with UAS operations is the task of transferring primary flight control among different control stations and pilots. In conventional multi-crew aircraft, pilots are co-located and clear roles are established between pilot-flying and pilot monitoring. During a flight, these roles can be readily switched using trained procedures and crew resource management principles to ensure a clear transition that can also be made apparent through direct observation and perhaps system features like left/right connected yokes.

However, having UAS pilots at different control stations introduces challenges to control handoffs. A unique feature of UAS is that control of the aircraft may be transitioned in-flight from one control station to another, and between radio links, such as from a satellite to a terrestrial radio system. The International Civil Aviation Organization (ICAO) uses the term "handover" when referring to the first of these transitions, and the term "switchover" when referring to a control link change. In many cases, both kinds of transfer occur at the same time, and handovers nearly always involve a transfer of control between pilots. Handovers have a significant level of pilot involvement, whereas switchovers may occur with little or no human involvement.

Control transitions have been identified as an area of increased risk in a range of industrial and transport settings, including aircraft maintenance, medicine, and air traffic control. Incident reports suggest that UAS handovers are times of heightened risk for issues such as inconsistent control settings, coordination breakdowns, and lost link events. The control of a long-endurance UAS may be transferred multiple times during the course of a single flight [43], with each occasion contributing to a cumulative level of risk.

Handovers can occur in a variety of ways. For example, the receiving control station will sometimes establish a telemetry link to the UAS prior to the handover, to enable the receiving pilot to establish situational awareness before taking control of the UAS. If the command link from the giving control station is disconnected before the receiving control station establishes a command link, then there will be a gap during which neither control station has a functioning command link to the UAS. This is sometimes referred to as a "break before make" handover. In other cases, the receiving control station may establish a command link to the UAS before the giving control station disconnects the telecommand link (referred to as a "make before break" handover). Each style of handover has benefits and disadvantages.

Handovers require special attention to ensure that the crew of the "receiving" and "giving" control station possess a shared understanding of the operational situation and that control settings are aligned between the two control stations. Due to the pilot workload entailed during a handover, and the potential for errors, handovers may be inadvisable during some stages of flight (e.g., approach and landing). Research is needed to inform guidance on the timing and conditions under which handovers should or should not occur.

2) Multi-aircraft control

Remote control also presents an opportunity to potentially alter the ratio of pilots to aircraft, which for conventional aircraft has been one or higher. There is great interest by industry in multi-aircraft control concepts that will enable lower proportions of pilots (and related "tactical operator" roles) by leveraging distributed teams and allocating human cognitive resources dynamically.

Such multi-aircraft control concepts are being explored, and are an active area for research (e.g., [44]). The research questions have evolved from simply "how many aircraft can a pilot handle?" to more complex questions such as, "in what ways can human teams and air/ground automation combine to maintain safety during non-normal events?" One fundamental challenge of the research is how to generalize results from specific scenarios, aircraft, automation, distributed teams, and procedures used in the analyses or simulations.

In particular, assumptions of automated functions and complementary assumptions of human roles and responsibilities have a significant influence on human operator tasks, information needs, and workload. For example a pilot who is supervising five aircraft, one of which experiences propulsion failure, could transfer control of the remaining four aircraft to a team member to focus on the off-nominal event, but other simultaneous events might necessitate a queue or prioritization that influences how control is transferred and to whom. As mentioned earlier, low altitude operations reduce the time available to deal with critical events. Task switching among humans has been shown to be difficult and error prone; for example, an increase in task switching tends to increase operator response times and the frequency of errors. Crew resource management among many team members that are not necessarily co-located can be complex, requiring clear communication of control transfer requests, acceptance, rejection, and the states of all relevant aircraft. Multi-aircraft operation during non-normal events presents a number of human factors challenges beyond conventional aircraft, and research is needed not only to understand human factors risks and mitigations in specific scenarios, but also to generalize results towards the development of future guidance.

H. Increased automation

New and increasingly capable and complex automation is a critical enabler of virtually all properties of UAS and AAM described in this paper. The introduction of automation can certainly address some human factors concerns, but can also create new ones [45]. In some cases, automation can introduce novel failure modes and impact human performance in ways that may be poorly understood.

When automation is designed to perform a task previously performed by humans, it is critical to understand any dependencies between the replaced task and any tasks remaining with the human to ensure that the human retains the relevant information, awareness, and skills to successfully perform the retained tasks. For example, as automated sensing capabilities continue to improve, tasks such as traffic/obstacle detection, intruder flight path estimation, right-of-way determination, basic avoidance maneuvering, and return-to-course decisions can be increasingly supported or performed by automated systems. Sensory information, however, also critically informs higher level human cognitive tasks such as situation assessment, problem detection, and replanning. Existing research suggests that learning benefits from "cognitively active" over "cognitively passive" behaviors (e.g., [46]). Research is needed to inform the design of systems that realize the benefits of increasingly capable automated sensing and perception systems while maintaining active engagement of the low-level human cognitive processes that are essential to support critical human macrocognitive functions (e.g., [47]).

Similarly, automation designed to prevent or mitigate human errors can create impoverished environments, oversimplified interfaces, and restricted ability to over-ride or take control from the automation. This can limit the ability of humans to demonstrate desired performance, such as anticipating, monitoring, and adapting to unexpected changes that are beyond the capability of the automation. Even in ultra-safe, well-studied systems such as conventional aviation cockpits, pilots intervene to manage aircraft malfunctions on 20% of normal flights [48], far exceeding (by a ratio of over 157,000 to 1) the frequency for which human errors are implicated in aviation accidents [49].

To date, human behaviors that routinely contribute to safety through preparation for and recovery from both expected and unexpected perturbations go largely unrecognized and unstudied, creating an ongoing challenge for the development of automation intended to replace humans, interact with them, or rely on them to intervene when the automation fails. Many human tasks that are considered for replacement by automation are supported by a complex array of human cognitive mechanisms that support not only task outcomes, but also processes for handling input variability, generalization from previous experience, etc., that ultimately enable human flexibility and graceful degradation. Automation designed to perform these tasks process information in ways that are either simplified or fundamentally different in other ways, relative to human information processing. As automated systems grow in complexity to support performance of complex tasks, the ability to understand and predict the behavior of these systems decreases [50].

Future human factors research is needed to inform decisions about what and what not to automate to support safe operations that include humans, automation, and increasingly complex interactions between them.

III. SUMMARY

This paper highlights opportunities for new human factors research based on emerging technologies and concepts of operation for future airspace operations. Although the pace of technology development is rapid, the need for human involvement in the system will remain robust for the foreseeable future, even as those human roles may change dramatically. Because these emerging technologies must interact with humans, it is critical that we understand how those interactions could and should happen, allowing for the design and operation of systems that can support and be supported by humans.

The research considerations described here are not intended to be prioritized or prescriptive, nor are they comprehensive. Rather, they are intended to illustrate an approach and way of thinking about human factors considerations derived from analysis of defining characteristics of UAS and AAM, the sufficiency of existing guidance, and the availability of relevant HF research.

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16. ABSTRACT This paper identifies some of the key human factors (HF) challenges when integrating Unmanned Aircraft Systems (UAS) and Advanced Air Mobility (AAM) into the civil airspace. Unique HF considerations—those which are derived from the key differentiating aspects of UAS/AAM compared to conventional aviation—are the primary basis for identifying HF research opportunities. By identifying what makes UAS and AAM fundamentally different from conventional aviation, from a human integration perspective, HF research can be targeted to effectively inform best practices, standards, policy, guidance, and regulations associated with aircraft and air traffic systems and operations. HF research areas are discussed within the following topic areas: Sustained low-altitude operations; loss of natural sensing; novel aircraft; novel operations; link management and lost link; link performance; distributed pilot teams; and increased automation. The identified research descriptions are intended to serve as illustrative examples of what research is fundamental, and why. They are not intended to prescribe, prioritize or exclude research.		
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