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Enabling Urban Air Mobility: Human-Autonomy Teaming Research Challenges and Recommendations

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Notions of "teaming" between human and machine agents have emerged as a critical area of research, focused not on how machines can think like people, but on how machines can help people think better. This paper details the efforts of a NASA committee to develop a research plan to address challenges and technology gaps associated with future aviation market applications, focused specifically on identification and implementation of capabilities and principles that facilitate humans and machines working and thinking better together. The NASA committee reviewed existing human-autonomy teaming (HAT) research, identified stakeholder community objectives, reviewed relevant concepts of operation, and identified a framework for establishing a coordinated, comprehensive, and prioritized research plan. The committee's findings with regard to the importance of HAT and HAT challenges for enabling future aviation market applications are described. This effort is intended to provide policy makers, engineers, and researchers with useful guidance for directing and coordinating HAT research activities.

I. Introduction

The National Airspace System (NAS) is a highly complex sociotechnical system that continues to grow and change at an increasing pace. The ever-increasing demand for flights has led to more crowded airspace and an accompanying need for more personnel, new classes of aircraft, and higher levels of autonomy. The NASA Transformative Tools and Technologies (TTT) Autonomous Systems (AS) Subproject was created to assist with the transition into higher levels of autonomy to enable new modes of air transportation such as Urban Air Mobility (UAM). In the first year, researchers with TTT-AS from all four NASA aero centers participated in exploration studies, identifying the challenges and technological gaps for achieving higher levels of autonomy in air transportation.

As the NAS continues to evolve, so, too, will the capabilities of the technologies that support operations within the NAS. As these technologies take on increasing responsibilities, humans and machines will be required to work together in new and different ways [1]. Notions of "teaming" between human and machine agents have emerged as a critical area of research, focused not on how machines can think like people, but on how machines can help people think better [2]. The goal of the TTT-AS Human Autonomy Teaming Planning Team was to identify the Human Autonomy Teaming (HAT) challenges and provide a comprehensive and prioritized research-driven approach to

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enable the success of future aviation market applications through capabilities and principles that facilitate humans and machines working and thinking better together. This paper details the results and method of the planning team's investigation. It is the authors' hope that this document may guide and educate policy makers, researchers, and engineers in the importance and challenges of HAT for enabling UAM.

II. Human-Autonomy Teaming

From the outset, a clear distinction must be made between systems described as *automation* and *autonomous*. Generally, automated systems are designated to accomplish a specific set of largely deterministic steps to achieve a limited set of pre-defined outcomes [3]. Importantly, automated systems are not self-directed [4]. Autonomous systems, however, are characterized by the capabilities of machines to "independently assume functions typically assigned to human operators, with less human intervention overall and for longer periods of time" [5] (p. 5). In comparison to automation, autonomous systems are both self-directed and self-sufficient [4]. Moreover, because of these characteristics, the algorithms supporting autonomous system decisions and actions are also non-deterministic in many cases. However, it should be noted that the terms "autonomy" and "autonomous system," referred to in the current paper, are more accurately labeled as *increasingly autonomous* [1] or *semi-autonomous* [6], as the goal of achieving full autonomy is still quite difficult [6] [3] [5]. From this perspective, although autonomous systems may be self-directed and independently assume human functions, these systems may still require human supervision, direction, and cooperation. The notion of an autonomous system acting independent of any human operator is neither desired nor technically plausible, as machine and human agents responsible for a range of functions will require varying degrees of inter-dependency, implying agents operate as teams [5].

The emerging field of HAT explores the various mechanisms by which humans and machines can work and think together [5] [7], where teams are "a distinguishable set of two or more *agents* who interact, dynamically, interdependently, and adaptively toward a common and valued goal/objective/mission" [8] (p. 4; the term "agents" was used in place of "people"). From this perspective, the goal of HAT is humans and autonomous systems *working and thinking better together*, where the focus shifts away from simple function allocation strategies (e.g., Men-are-Better-At/Machines-Are-better-At, [9]) and instead focuses on re-structuring the team processes. The human-automation interaction literature points to potential pitfalls associated with some automation implementation strategies (e.g., humans as system monitors often lead to out-of-the-loop unfamiliarity, surprising mode transitions, and skill loss; [10]). Nevertheless, a comprehensive and prioritized research-driven approach to enable the success of future aviation market applications through capabilities and principles that facilitate humans and machine working and thinking better together is still required. One such aviation market application that will require such an effort is UAM.

III. Urban Air Mobility

UAM is defined as "…a safe and efficient system for air passenger and cargo transportation within an urban area. It is inclusive of small package delivery and other urban unmanned aerial system services and supports a mix of onboard/ground-piloted and increasingly autonomous operations" ([11] p. 4). Thipphavong et al. [12] describe early UAM as an extension of current passenger-carrying helicopter operations. Initially, UAM airspace will be characterized by infrequent flights traveling fixed routes between a small set of takeoff and landing areas. These early UAM operations will employ human pilots with air traffic control (ATC) providing services and will likely be similar to current visual flight rule (VFR) operations. Mature UAM airspace, however, will be characterized as increasingly dense, with frequent flights that travel among an expanding network of takeoff and landing areas (i.e., vertiports) using fundamentally different aircraft, electronic Vertical Takeoff and Landing (eVTOL) vehicles [12]. As operations increase, to maintain the needed economies of scale to achieve affordability, so too will the number of pilots required to keep operational pace. One concept for UAM operations acknowledges that this increase in pilot demand will lead to a shortage of qualified pilots because the training process of a commercial pilot is relatively expensive and time-intensive [13]. As a result, UAM pilots may have minimal training and little or no prior experience operating aircraft. To this point, NASA has identified *inadequate pilot training to maintain safety margins* as a potential hazard in the UAM paradigm [12]. To account for the limited number of trained pilots coupled with high density/tempo operations, many in the research and development community are proposing that UAM operations be heavily supported by autonomous systems to enable functions ranging from fleet and resource management to vehicle control [13] [12]. Indeed, in recent decades, automation has become increasingly sophisticated and ubiquitous in civil aviation [14]. Yet, autonomous systems represent a significant evolution in automation, which has generally been limited in functional scope and capability [6]. To support safe and efficient UAM operations, HAT needs to be a central research focus.

IV. Method

A. Reviewed Existing HAT Research

The TTT-AS Human Autonomy Teaming Planning Team was formed with the goal of establishing guidance recommendations for human-autonomy teaming research. As part of committee planning efforts, an exhaustive literature search and review [15] [16] [5] provided a set of key fundamental topic areas that were categorized into six superordinate research categories: (a) teaming models; (b) contingency management; (c) shared situational models; (d) trust calibration; (e) methods, metrics, and measurement; and (f) paths to operational approval. The represented categories are not unique to HAT but provided the research space necessary to target identified needs specific to the content domain. Each specific HAT research topic (e.g., bi-directional communication) is postulated to be comprised of one or more of these six superordinate research categories.

B. Leveraged Identified Stakeholder Community Objectives for Aviation Autonomy

Through a partnership with NASA stakeholders, a set of community operational objectives for aviation autonomy has been established that provides guidance and directions for NASA aeronautics programs [17] [18]. To achieve these envisioned set of autonomy strategic goals, HAT was considered in terms of research need toward a path of achievement of the community operational objectives, which is delineated in Table 1 below.

Table 1. Community Operational Objectives for Aviation Autonomy and HAT Research Need

Community Operational Objectives	HAT Research Need
Enable aircraft without an onboard pilot to routinely operate in the NAS	Will require coordination between off-board pilot and onboard machine agent
Remove the need for the current regulatory paradigm that requires a pilot for every passenger aircraft	There is no realistic timeline for the development of machines with all the required capabilities, so will require human interaction for the foreseeable future
Achieve an order of magnitude more vehicles than operators	Will require appropriate interaction between vehicles and operators, whose function migrates from being pilots to being supervisors/managers
Enable order-of-magnitude increases to airspace system capacity, unconstrained by human workload limitations	System and agent capacity limitations are partially a function of design. New strategies for multi-agent teaming could increase airspace capacity while mitigating human workload limitations
Enable air transports to be piloted safely by a single operator	Will require appropriate interaction between machine agents and operators, and require methods of safety assurance that account for these interactions
Enable new emerging market pilots to receive certification with order-of-magnitude reductions in training	Training reductions will require increasingly capable machines, with which the pilots must interact
Enable aircraft to auto-land anywhere and under nearly any conditions	The technical capability to auto-land is currently available for restricted conditions and the impact on human-autonomy interaction remains unexplored and untested

C. Identified UAM-HAT ConOps (RSO, SVO, UAM Airspace)

The success of UAM is predicated on cultivating an ecosystem for UAM that includes manufacturers of eVTOL aircraft; designers of vertiports and/or takeoff and landing areas; and researchers for new airspace integration concepts, technologies, and procedures needed to conduct UAM operations safely, orderly, and expeditiously alongside other airspace users [12]. HAT issues have been identified throughout many of the critical paths to implementation of UAM [19]. For example, the UAM community has identified a need to evolve from requiring expert pilots onboard each aircraft to remote supervision of multiple vehicles by *human* ground control operators. The UAM Maturity Levels

(UML) range from UML-1 to UML-6 requiring three transition phases from pilots to supervisors: (a) Phase 1 - simplified, automation-enabled single-pilot operations; (b) Phase 2 – remote operators and increasing operational densities; and (c) Phase 3 – Many-to-One supervision [14] [20] [21]. Each of these phases has numerous technological and operational human-autonomy challenges. Therefore, the application chosen by the committee for HAT research focus was UAM; specifically the concepts of operations of (a) simplified vehicle operations (SVO); (b) Remote Supervisory Operations (RSO) or m:N (m - operator, N – vehicle); and (c) UAM airspace.

SVO is the use of automation/autonomy and complementary technologies, coupled with human factors best practices, to reduce the quantity of trained knowledge, skills, abilities, and experience that the pilot or operator of an aircraft must acquire to operate the system at the required level of operational safety. SVO maps aircraft certification to pilot/operator training requirements that must show demonstrated capability to achieve a higher reliability level at performing a function than an "average" pilot across normal, off-nominal, and abnormal operating contexts. The key idea of SVO for UAM is the need to reduce the training footprint because of costs and projected shortage of qualified pilots to meet envisioned future on-demand mobility needs. Aircraft manufacturers and operators may implement more autonomous functions, or implement fewer autonomous functions and accept fewer operational restrictions; the functions that would normally be the responsibility of the pilot-in-command (PIC) must be assigned either to a human, or to the automation, or through a shared "teaming" capability. If the human is responsible, s/he must be given the appropriate training; if the automation is responsible for the safe execution of the function, it must be certified to achieve a level of reliability that is better than the comparable human PIC performing the function [22]. Given the above, significant human-autonomy challenges concerns SVO to include roles and responsibilities, information requirements, novel displays and interfaces, design of vehicle / augmented controls and functional requirements, pilot training, operational requirements (e.g., urban, weather, winds, fleet management), contingency/emergency management, and certification (see Section V.A below). How to design future simplified vehicle concepts to enable teaming, and foster "cognitive collaboration" where the human pilot and the autonomy do better together, represents a significant HAT research challenge for SVO.

RSO represent the second concept of operation for UAM targeted for its unique and substantial HAT research needs. The community operational objectives for aviation autonomy emphasized need for transformation toward supervisory remote control of air vehicles. The m:N concept is a defining end goal of UAM wherein pilot requirements are reduced through SVO, in early phases, leading ultimately to control of multiple urban air vehicles by one or more ground control operators (i.e., many-to-one supervisory control). RSO is a complex challenge involving issues of technology readiness, safety, certification, acceptance, and HAT [19]. Section V.B. below describes the myriad research challenges and opportunities availed by the UAM concept of operation.

UAM airspace represents the final concept of operation for UAM identified for HAT research focus. Although having significant overlap with other concepts of operations for UAM, it was chosen to be a separate research emphasis because of the complexities involved in HAT across multiple autonomous airspace system applications (e.g., unmanned aircraft system traffic management [UTM], UAM, m:N; autonomous air freight/cargo; increasingly diverse operations) [11]. Research challenges include what procedures, displays, tools, aid, and information shall be required; concerns of cybersecurity; how to ensure the reliability, robustness; and resilience of these systems; roles and responsibilities for humans and autonomy; and how best to design the technologies and capabilities that support HAT. Section V.C. details the substantial volume of research challenges that will need to be solved before the potential of UAM vision can be realized.

D. Considered the Range of Methods for Scientific Discovery

The scope of research challenges of HAT for UAM concepts of operations are significant and numerous, requiring a coherent, comprehensive, and cohesive framework for strategic thinking of needs across a varied and diverse portfolio of research issues, challenges, and requirements. A model of scientific inquiry was adapted based on the field of translational medicine (e.g., [23]). The concept of "translation" involves the process of turning observations in the laboratory, clinic, and community into interventions that improve the health of individuals and the public — from diagnostics and therapeutics to medical procedures and behavioral changes. "Translational science" is the field of investigation focused on understanding the scientific and operational principles underlying each step of the translational process [24]. The goal of translational research is to translate, or move, basic science discoveries more expeditiously into practice. Similarly, the field of HAT, although relatively nascent, has foundations (i.e., foundational) in the significant volume of human-human teaming and human-automation interaction literature. Furthermore, there exists a growing body of work in direct applications (i.e., applicational) of autonomous technologies that have contributed to knowledge of HAT.

Translational research is often classified according to which stage of translation it falls into typically moving from TO (basic science research) to T4 (translation to the community). Adopting this framework [24], it was modified to more clearly distinguish between stages of scientific discovery for HAT (Figure 1):

- Foundational (F) Basic Science Research - Advancement of science and knowledge base through exploratory, descriptive, and explanatory research
- Translation (T1) to HAT - Application of science and theory for research and development of HAT
- Translation (T2) to Emerging Markets - Translation of fundamental and domain-specific knowledge to emerging markets
- Translation (T3) to Autonomy Applications - Industry innovations of emerging autonomy applications
- Applicational (A) Solutions - Delivery of autonomy community implementation solutions

Through this framework, knowledge is learned and shared bi-directionally across the methods of scientific discovery (see Figure 1). Figure 2 graphically shows the continuous research loop that is formed from the human-autonomy research categories (outer loop) and methods of scientific discovery (inner loop) that transforms ideas into actions in the form of new knowledge and implementation solutions for the HAT application.

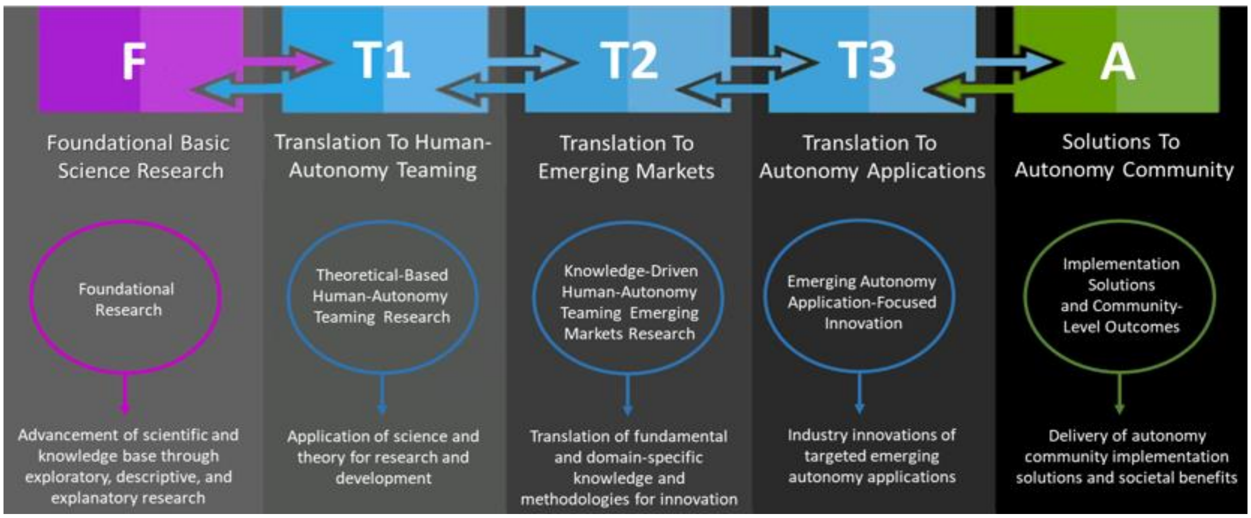

Figure 1. Methods of Scientific Discovery

Figure 2. The Human-Autonomy Teaming Research Loop

V. UAM-HAT Research Challenges

Based on extensive reviews of the literature [5] [15] [16], six overarching HAT research challenges were identified:

- **Teaming models**: What models of multi-agent interaction should be used, and how can we evaluate them?
- **Shared situation models**: How can a common knowledge base and capability for intent inferencing between human and machine agents be established?
- **Trust calibration**: How can inter-agent trust be appropriately built, calibrated, and leveraged to establish roles, authority, and transitions of control?
- **Contingency management**: How can we ensure that human-machine teams retain or improve upon current capabilities to sustain operations under expected, uncertain, unanticipated, and unpredicted conditions?
- **Performance measurement**: How can human-machine team performance be measured and leveraged to enable ongoing system performance improvements?
- **Paths to operational approval**: What are the viable paths to certification and operational approval of human-machine teaming concepts?

These research questions, although fundamental to the successful implementation of HAT principles, are not necessarily unique to HAT. Furthermore, exploration of specific HAT concepts of operation may suggest more specific research challenges that fall under one or more of these overarching questions. In the following sections, three HAT concepts of operations relevant to UAM are described, along with HAT research challenges that must be addressed within each of those concepts: SVO; RSO; and UAM Airspace.

A. SVO Research Challenges

The UAM vision calls for aircraft without an onboard pilot, but it is recognized that the pathway towards that objective may start with professional commercially qualified pilots. SVO research will investigate how to safely transition to reduced pilot expertise and training requirements for new classes of aircraft and operational environments. Automation to support pilots has been in use in aircraft for over 100 years, but ideas proposed by industry will require fundamental changes to design and evaluation methods to allow for safe operation without stifling innovation.

The proposed SVO line of research will examine several issues, including:

- How to assess simplified flight controls? New aircraft entrants are proposing new methods for controlling aircraft with a goal of reducing pilot training and expertise requirements. How do we ensure safety with these new concepts?
- How to evaluate novel operations? Some proposed UAM operations involve novel concepts in addition to novel automated systems. How do we characterize hazards for these operations?
- How to evaluate the combined aircraft, pilot, and flight controls? Current evaluation processes assess vehicle performance separately from aircraft automation and operational procedures. The addition of automated systems will require new methods of integrated evaluation.
- How can we assess contingencies and emergency situations to ensure coverage in Human and Automated system teams? Where and how do humans contribute to safety?
- Can we develop aircraft that are easier to fly? If so, how do we safely reduce pilot training and expertise requirements?
- Can we effectively train pilots as automated system supervisors? Current evaluation criteria were not written with automated systems operation in mind, and past addition of automated systems has not reduced overall. How do we determine the appropriate evaluation criteria?

B. Remote Supervisory Operations (RSO) Research Challenges

From the time that Orville Wright flew the Wright Flyer to the F-35 Lightning fighter jet, aviation technology has progressed dramatically. However, one aspect remains the same. There is one PIC flying one aircraft (a ratio of 1:1). Many commercial aircraft have two pilots and, in the past, flight engineers, so the ratio of pilots to aircraft can be 2:1 or 3:1. However, there is always a single PIC so the ratio to date has always been 1:1.

The emergence of remotely piloted aircraft systems (RPAS) changes the physical arrangement from the pilot located in the aircraft to being located at a ground control station. RPAS enables the ability for a single PIC to control multiple aircraft. Coupled with increases in autonomous capabilities, it has become technically feasible for a single operator to control multiple aircraft (1:N).However, many issues are raised by such an arrangement.

The proposed RSO line of research will examine several issues, including:

- Can one operator control multiple aircraft safely and efficiently in the NAS? How many?
- Can multiple operators controlling multiple aircraft enhance or enable that operation?
- How do these multiple operators work together to share the load, communicate, hand-off control, etc.?
- How do we certify this operation?
- What information does the operator need? How should the information be displayed? How do we design for bi-directional communication? Transparency? Shared situation awareness?
- Is there predictive information available in the system and how to support HAT to allow operators to schedule tasks to level workload (e.g., playbook, working agreements)? How can this predictive information be displayed (e.g., pilot directed interfaces)?
- What is the teaming model and architecture for RSO that enables humans and autonomy working and thinking better together?

C. UAM Airspace Research Challenges

The safety and efficiency of autonomous UAM relies on the successful design and implementation of collaborative systems to perform autonomous air traffic management. With human workload identified as the primary impediment to achieving scalability, the UAM concept of operations asserts that active management of all nominal operations be allocated to automation and vehicle operators, including giving automation the authority to approve or deny airspace access. In early UAM research and development as well as during the predecessor project, UTM, the role of the human has been improperly dismissed. In situations of uncertainty and contexts that fall outside the capabilities of automation, airspace users must be able to bypass automation and communicate with a human airspace manager. In the most extreme cases, such as those where loss of life is inevitable, a human must intervene. If engaged only at the moment of an off-nominal event, the human airspace manager would most likely fail to solve the problem; thus, it is imperative that an increasingly autonomous airspace system design, despite being autonomous, be centered on the human to maintain human engagement, or quickly onboard the human to re-engage when needed. HAT concepts provide new options for addressing this and many other airspace management issues, including:

- ATM coordination in mixed digital and voice communication operations
- Data exchange and communication across ecosystems
- Control airspace access gaming
- For heavy traffic and complex urban environments, sequencing tasks for evening nominal operations may be handed back to the human
- Verifying source, availability, and reliability of data for decision-making
- Maintaining situation awareness for human airspace supervisors
- Controlling the pace of system failures to create reasonable time horizons for the return of failed autonomous functions to the human
- Dynamic switching between procedure for clearances from ATC vs. autonomous airspace system

Early autonomous airspace research would draw from existing human-computer interaction principles and tools that reflect some general characteristics of effective teams. Advancements in foundational research efforts will inform further airspace work by providing a framework, as well as capabilities and principles that more consistently characterize HAT. The proposed airspace management line of research will examine several issues, including:

- What procedures, displays, tools, aids, and information are required to support human-automation as well as human-human teams and individual humans?
- What are the roles and responsibilities of humans and autonomy (e.g., Airspace Operations Manager, Traffic Management Service Supplier)?
- What factors influence decision-making for airspace services?
- What uncertainties or limits of automation will require input from the human?
- How can artificial intelligence be designed to highlight/filter relevant airspace data?
- How can proposed HAT approaches be used to slow the pace of system degradation thereby allow humans time to become engaged with the problem?
- How can we structure the human-automation team structure to recover the airspace system from graceful degradation?

- What are the research challenges, issues, and needs for airspace access and security management (including cybersecurity risks)? How to best design for disruption management? Airspace constraints? Contingency management?

VI. Conclusion

HAT represents a new way of thinking about how humans and machines interact, focused on how human and machine capabilities can best complement one other. While many challenges must be addressed to achieve the full potential of HAT, that potential can enable new aviation markets and new paths forward in aviation safety and efficiency. The goal of this effort was to provide a comprehensive and prioritized research-driven approach to enable the success of those future aviation market applications by leveraging HAT principles that facilitate humans and machines working and thinking better together. This document describes the importance of HAT and HAT challenges that will need to be explored to enable autonomous UAM. TTT-AS is using the guidance described in this document to direct research in addressing these challenges. It is the authors' hope that other policy makers, engineers, and researchers will find this guidance useful for directing and coordinating HAT research activities.

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