Enabling Novel Collaborative Control Paradigms between Humans and Machines in Electric Vertical Takeoff and Landing (eVTOL) Aircraft

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ABSTRACT

Electric Vertical Takeoff and Landing (eVTOL) vehicles undergoing advanced air mobility (AAM) operations feature increasingly autonomous systems (IAS) with non-traditional role allocations. Ensuring the safety of these operations and their novel human–machine teaming (HMT) paradigms requires an appropriate body of knowledge created through relevant, reproducible research. In this paper, we briefly examine the meaning of teaming; current regulation, standards, and guidance; and the knowledge required to build resilient HMTs before turning our attention to how this knowledge is being created by recent research and what conclusions or recommendations can be made. We identify the need for further research into the holistic performance of HMTs, the effect of novel allocations of roles between humans and machines, the ability of humans to provide resilience to unforeseen dangers when acting as a part of these teams; and the characteristics required for clear, timely, and accurate communication between the humans and machines. This work is done in the context of eVTOL aircraft with an indirect flight control system (IFCS) undergoing urban air mobility operations.

INTRODUCTION

Electric Vertical Takeoff and Landing (eVTOL) vehicles incorporate more automation and/or autonomous functions than are in use today in helicopters (Refs. 1, 2). The verification, validation, and certification of these systems is a critical barrier to their adoption and use in the national airspace system (Ref. 3). There is a shifting locus of control for safety critical decision making from humans to machines in these vehicles (Refs. 4, 5), and the safety analyses and V&V techniques used to assure them will not be able to rely on the current human-centric approach to ensuring safety. For example, all currently proposed eVTOL concept aircraft use indirect flight control systems (IFCS). It is important to recall that these vehicles are designed for either single pilot operations (SPO) or autonomous operations over a densely populated urban area at a low altitude with reduced separation criteria. The integration of state-based controls with unconventional human machine teaming (HMT) paradigms will catalyze the development of new pilot automation, novel flightdeck technologies (i.e., inceptors), and innovative displays (Ref. 6). This will create challenges in the development and evaluation of eVTOL IFCS aircraft and their automation, pilot (or operator) training, and operational procedure development. The ability of the novel HMT paradigms to create safety producing behaviors is especially critical during precision maneuvers such as takeoff, landing, and hovering at elevated airports where traffic, wind, and turbulence may prove problematic (i.e., crab-slideslip landing in crosswinds), which may not be flyable without novel displays and automation aids to enhance situational awareness (Ref. 7). For example, a single pilot interacting with advanced automation to control an aircraft may have advantages a single pilot of a less-automated aircraft does not but will lack the benefits of a second pilot and contemporary crew resource management (CRM). Because of this, assessments of crew performance, crew impact, and related aspects of the aircraft design will need to account for these system's novel human–machine teaming (HMT) paradigms. Likewise, a single operator overseeing several high-velocity, high mass automated aircraft would interact with those aircraft differently than either a contemporary pilot or airline dispatcher, leading again to different safety concerns and obligations.

This paper investigates different HMT paradigms and the research that might underpin evidence-based evaluation, assessment, and safety assurance of eVTOL IFCS aircraft and

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their operations. We draw our findings and base our recommendations on a multitude of sources. Firstly, research performed under the NASA research announcement (NRA) entitled "Assuring Increasingly Autonomous Systems with Non-Traditional Human Machine Roles" forms the keystone for this work. This NRA ran for the past four years and focuses on the evaluation and safety assessment of novel human-machine teaming paradigms in an urban air mobility setting. Secondly, we incorporate insight from current regulation, industry consensus standard-making, and policy and advisory material from civil aviation authorities (CAAs). We also draw on the current state of the art and practice for the use of novel human–machine paradigms in industry, government, and academia.

WHAT DO WE MEAN BY 'TEAMING'?

We use the term *human–machine team* (HMT) to describe one or more machine agents and one or more human agents working in tandem interdependently to achieve a collective goal (Ref. 8). A *machine agent* is non-organic and powered by a computational algorithm (Ref. 8). To function in the role of a "teammate" with a human, a machine system must be able to perform its roles with some degree of operational independence (Ref. 9). Teammates need a level of autonomy—freedom to act and decide independently of others and the capabilities to scan their environment, analyze it, make decisions based on their assigned goal, and learn from what happens)—that exceeds current systems (Ref. 9). *Interdependence* can be an attribute of an activity (i.e., dependence upon another's tasks in one's own role) or an outcome (i.e., the extent to which team outcomes have consequences for the individual). Interdependence requires that humans and machine agents leverage their unique capabilities and information for the good of the other team members and the team as a whole (Ref. 8). That is, work is performed better in, or even requires, the presence of the other agent(s).

Creating successful human–machine teams

Machines are conventionally treated as tools. But when interactions with them are fluid, highly interdependent, and aligned toward a collective goal, and when the machine appears to possess the capabilities to act independently, adapt, and learn, this can engage propensities for social cooperation in the human agent (Ref. 10), elevating the machine to a teammate. Sustaining safe operations in complex, unbounded, and dynamically changing environments requires consideration not only of failure prevention, but also preparing for and recovering from both expected and unexpected failures. While this is something that humans successfully do routinely, these behaviors have not historically been well-documented and are poorly understood. Recognition of and support for these common behaviors is necessary to ensure effective teaming. Given the criticality of human propensities for social cooperation in establishing team situations, it is appropriate to consider the decades of empirical research on human teams as one part of a foundation for HMT research, but the linkage from human-human teaming to human-autonomy teaming "will not be a one-to-one transfer of knowledge" (Ref. 8, p. 1).

Rising authority-responsibility mismatches in HMTs

The rise in the allocation of functions formerly performed by humans to machines has led to authority–responsibility mismatches: one agent is authorized to perform an activity, but a different agent is responsible for its outcome. Such mismatches demand monitoring by the responsible agent and impose additional task(s) on that agent (Ref. 11). For example, previous studies (Refs. 12, 13) identified controllability issues in eVTOL aircraft when transitioning from wingborne lift to vertical lift, leading to the proposal of an automated "hover" mode. However, there are multiple HMT paradigms that can be proposed for this hover mode (e.g., automatically engaged below certain groundspeed, automatically commanded deceleration rate, automatically commanded deceleration to hover point, etc.), some of which may affect the pilot's situational awareness (and their ability to intervene) and require frequent monitoring of the displays and automation to maintain safety.

How we should allocate tasks to empower humans (rather than set them up to fail) turns on whether humans are inherently "bad" at monitoring. The oft-cited Fitts report (Ref. 14) states that humans are poor *passive monitors*, not poor monitors generally. Thus, one should distinguish poor performance resulting from (design independent) fundamental human cognitive limitations versus poor performance resulting from (design dependent) environments, tools, or tasks that are misaligned with how human cognitive systems work.

FEDERAL AIRWORTHINESS STANDARDS AND CERTIFICATION

New civil aircraft types must receive a *type certificate* before instances can be flown. *Civil aviation authorities,* such as the US Federal Aviation Administration (FAA), *approve* aircraft systems after applicants demonstrate that they have complied with applicable regulations in accordance with a negotiated *certification basis* (Ref. 15). These regulations can include 14 CFR Part 23, 25, 27, or 29 in accordance with aircraft type. Certification of an aircraft's type follows and is supported by approval of its systems.

One general-purpose element of the regulations addresses equipment failure (e.g., section 1309 of 14 CFR Part 25). Generally speaking, these regulations require designs to (a) limit the rate at which equipment, systems, and installations enter states that could lead to loss of the aircraft and (b) alert the crew to such failures to facilitate corrective action. Development assurance practices such as those described in ARP4754B and ARP4761A are recognized as a means of compliance with 14 CFR Part 25.1309 (Refs. 16–19).

Another general-purpose element addresses designing systems and equipment to facilitate their use by the flight crew (e.g., 14 CFR Part 25.1302 or 14 CFR Part 23.2600). These

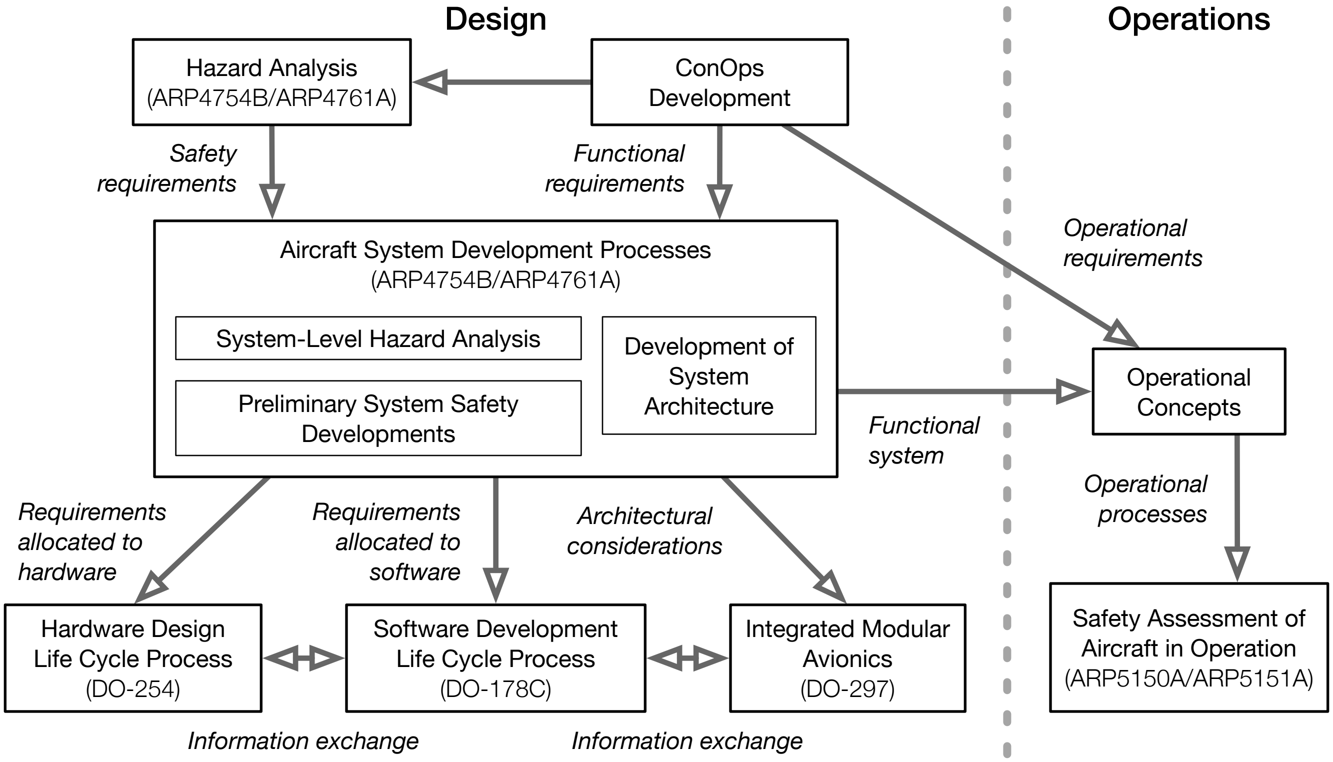

Figure 1. Consensus standards used in the traditional aircraft development and safety assurance lifecycle

regulations require designers to make flight deck controls and displays clear, unambiguous, and accessible and to enable awareness of the effects their actions might have. Section 1302 of 14 CFR Part 25 requires the behavior of installed equipment to be "predictable and unambiguous" and "designed to enable the flightcrew to intervene in a manner appropriate to the task." Designers must also, to the extent practicable, design equipment so that appropriately skilled flight crew can manage errors resulting from foreseeable, non-malicious use of that equipment. These requirements have analogues in the parts applicable to other types of aircraft. Crucially, all these requirements implicitly assume traditional pilot–aircraft relationships wherein the aircraft is a tool of a pilot or pilots who are responsible for its safe operation.

Consensus standards such as ARP4754B and ARP4761A were written to address traditional airplanes and rotorcraft and might require adaption for use with novel vehicles and operations (e.g., eVTOL in UAM) with non-traditional HMT paradigms (Refs. 16, 17). Figure 1 depicts how these standards fit into the traditional aircraft development and safety assurance lifecycle. These standards take into account both the possibility of crew mitigation of failure conditions and the deleterious effects of those failures on humans aboard the aircraft. Functional hazard analysis (AFHA and SFHA as defined in ARP4761A) requires analysts to (a) describe the expected crew response to failure conditions and (b) describe the impact of failure conditions on cockpit crew and other aircraft occupants as well as impact on the aircraft itself as a machine (Ref. 17). The analyses underpinning these descriptions is done by a separate human factors team. Again, a traditional pilot–aircraft relationship is implicitly assumed.

Following the 737 MAX accidents, airworthiness authorities asked SAE's S-18 (development assurance) and G-10 (human factors) committees to address such human considerations in the aircraft development and safety assessment processes (Refs. 20, 21). The relevant communities of practice understand that neither crew reactions to a failure condition nor the impact on crew are always as designers anticipate. Where history is not an adequate guide, aviation human factors specialists may need to assess crew reactions through, e.g., pilot-in-the-loop simulations. But while airframers conduct such analyses per their internal processes, there is not a well-established industry consensus best practices document describing the process of validating human–machine interactions of the aircraft safety assessment or establishing what kinds of justification for assessments are needed in those cases. To begin addressing this, the SAE S-18H subcommittee has begun to draft reports describing the interactions between human-factors and development assurance practitioners, starting with interactions related to the AFHA and SFHA processes (Refs. 16, 17, 22).

Because novel HMT concepts represent a departure from traditional cockpit allocation of tasks to humans and machines, we can expect an increase in the number of crew response and impact inputs to AFHA and SFHA that cannot be established solely by reference to long-established history. The inputs in these cases will need to come from dedicated research studies and fresh empirical evidence. For instance, NASA is currently conducting the Automation Enabled Pilot studies centered around the development of industry representative aircraft, aircraft automation, training, and operational procedures for eVTOL IFCS aircraft undertaking urban air mobility (UAM) operations (Refs. 7, 13). The collection of safety-relevant data, through simulation and operational evaluation, is one of the hallmarks of this effort.

THE MISSING KNOWLEDGE NEEDED TO BUILD RESILIENT HMTS

Traditional design paradigms with well-developed roles and responsibilities for human crew help to engineer resilience into the system for when "unknown unknowns" are encountered. However, there is scant research that would enable designers to fully predict the effect of altering the roles and responsibilities of human and machine, especially under conditions that are unforeseen, unplanned, or unanticipated. Systems that operate successfully in dynamic environments for which the range of possible states or conditions is not fully defined exhibit *resilient performance* (Ref. 23).

Fielded systems have largely relied upon humans to provide this resilience in the event of automation failure or a situation not anticipated or accounted for by automation designers. Indeed, in "major incidents" in which pilot interventions successfully mitigated potentially catastrophic events, equipment malfunctions were identified as a threat in 55% of those events, and there was no defined checklist or defined procedure to address those equipment malfunctions in over 45% of those cases (Ref. 24). This capacity for resilience must be preserved as machines increasingly perform tasks once performed by humans.

While the study of human error provides some information about underlying cognitive mechanisms and boundary conditions of human performance, there is limited data on how humans succeed, and the systematic study of human resilient performance is an emerging area of research. Since humans are the predominant provider of resilient performance, this dearth of knowledge means that there is little data to inform development of such capabilities in eVTOL IFCSs. Thus, eVTOL IFCSs systems will continue to rely on humans to provide resilience for the foreseeable future.

A critical challenge, therefore, in the design of eVTOL IFCSs is to determine which tasks should or should not be allocated to which agents and how and when to make those allocations. With respect to sustaining the capability for human resilient performance, it is necessary to consider interdependencies across tasks, such that task allocations to the machine agent enhance, or at least preserve, the capability for human resilient performance rather than reduce it. Such task allocations might conflict with those derived using substitution-based function allocation strategies (e.g., "Humans-Are-Better-At/Machines-Are-Better-At" (Ref. 14)), which can paint a design-invariant picture of human capabilities and limitations without an underlying theory of why human performance might be "good" or "bad." Furthermore, such function allocation strategies put the focus on human *or* machine, without consideration of human *and* machine, and thus the processes that support multi-agent interaction.

HMT requires juxtaposing the most complex algorithmic models in existence with the most complex natural systems in existence, and accounting for how they affect and are affected by each other in contexts that are unbounded, high consequence, and defined by uncertainty. Unprecedented challenges such as this require unprecedented solutions—new paradigms of design and development. Just as HMTs represent a union of humans and machines, the research and development necessary to develop successful HMTs for eVTOLs (with IFCS) undergoing UAM operations will require a coordinated interdisciplinary effort (Ref. 25).

Thus, the following knowledge challenges persist in the design of resilient systems: (1) Limited data on how humans succeed in engendering resilience (i.e., not just looking at how humans fail, but what they do to make systems safe in everyday operations); (2) Limited understanding of how task allocations of functions between humans and machines foster human resilience (i.e., what interdependences between tasks help require a specific function allocation to enable human resilient performance); and (3) Lack of interdisciplinary research and interaction needed to characterize how humans and machines affect each other when performing complex, safety-critical functions in unbounded and uncertain contexts.

INTERDISCIPLINARY HMT RESEARCH

In this section, we highlight some recent research, conducted under NASA's auspices, that has begun to address the safety implications of novel HMT paradigms for eVTOL aircraft undergoing UAM operations. Three research teams executed efforts under the NASA NRA entitled "Assuring Increasing(ly) Autonomous Systems with Non-Traditional Human-Machine Roles":

1. A team from PI Pennsylvania State University (Penn State) with Co-I Iowa State University (Iowa State) (PIs: Prof. Amy Pritchett and Prof. Cody Fleming) executed *Assuring Increasingly Autonomous Capabilities with Novel Delegations of Authority and Responsibility* (Jan. 2021–Dec. 2024).

2. A team from PI Collins Aerospace with Co-Is Florida Institute of Technology (FIT) and Soar Technologies, Inc. (PIs: Dr. Jennifer Davis, Prof. Siddartha Bhattaycharyya, and Mr. Randall Jones) executed *Assured Human Machine Interface for Increasingly Autonomous Systems (AHMIIAS)* (Feb. 2021–Mar. 2023).

3. A team from PI Massachusetts Institute of Technology (PI: Prof. Nancy Leveson) executed *Modeling and Analysis of Safety in New Human-Automation Teaming* (Sep. 2021–Aug. 2024).

Each research effort above addresses a different piloting paradigm and examines the pilot's ability to intervene when necessary in the context of the operation studied.

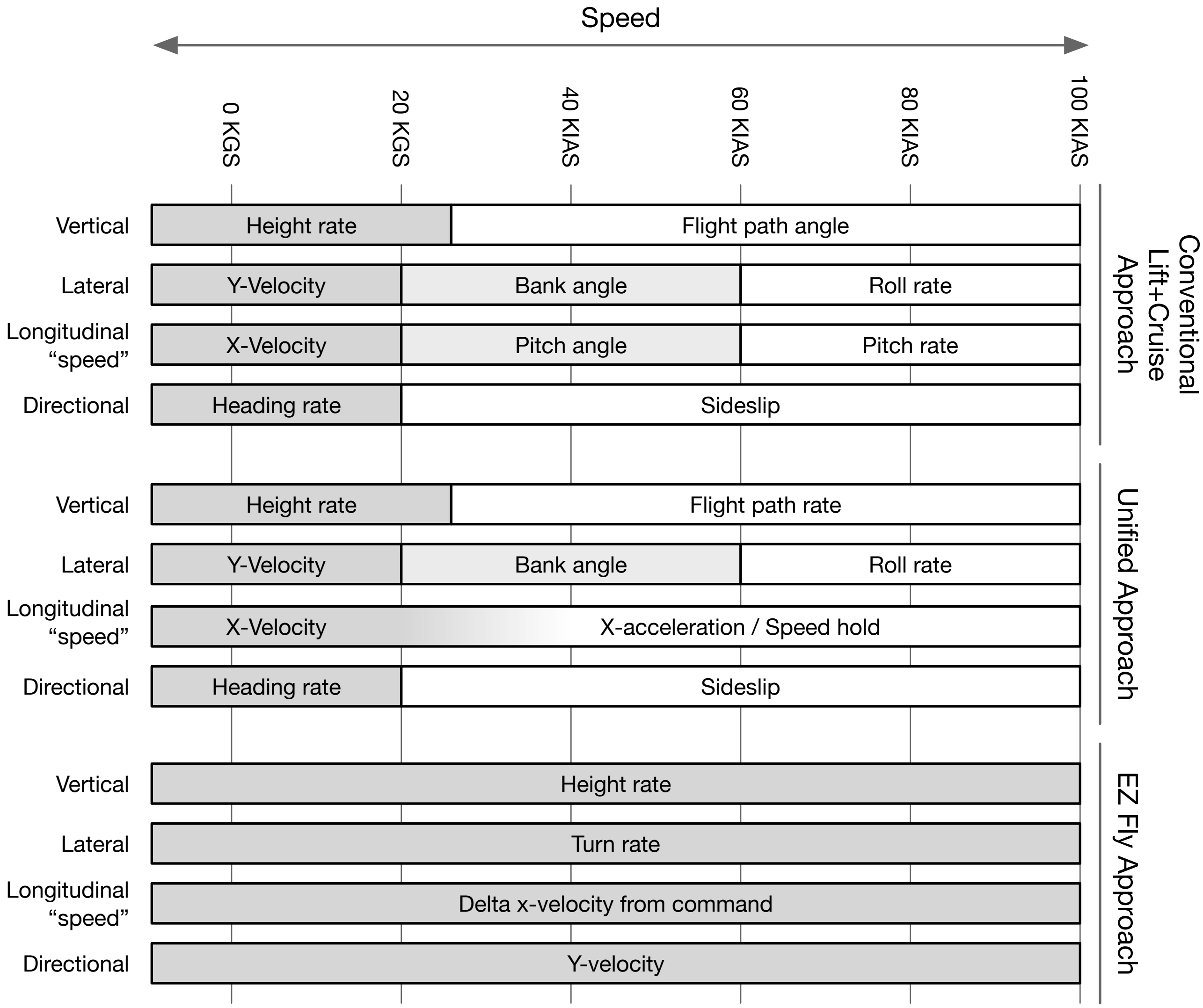

Figure 2. Increasingly autonomous paradigms for eVTOL control

The research performed by the Penn State team is done in the context of a last-mile delivery service using a small UAS rotorcraft to make on-demand trips. The remote operator of the sUAS is beyond visual line of sight for the duration of the operation, and the potential use of multiple operators and the implications of handoffs between operators is discussed.

The Collins Aerospace team embraced a short haul rural-urban passenger carrying use case, whereby a large, passenger-carrying VTOL (i.e., AW-609) could be used to transport individuals from rural (or exurban) locations to the city center and back. An airline transport pilot with a powered-lift category rating was assumed to be onboard the aircraft, with a conventional Lift+Cruise control approach (Ref. 12) being used (see Figure 2).

The MIT team examined an urban-air mobility mission in the context of an on-demand, urban mission taking place in an airspace containing multiple classes (i.e., Class B, Class E, Class G, etc.). The UAM aircraft was assumed to have an operator onboard, however, the approach taken was to assign responsibilities to the pilot/operator, thereby allowing for multiple pilot control paradigms to be examined, such as the Unified Controls approach and the EZ Fly approach (see Figure 2). For further details on these approaches, please see (Refs. 7, 12, 13).

Assuring Increasingly Autonomous Capabilities with Novel Delegations of Authority and Responsibility

The Penn State / Iowa State research comprised two threads. The first thread, performed by Penn State, concerns the ability of well-designed HMTs to generate safety producing behavior in UAM operations. The second thread, performed by Iowa State, focuses on the application of safety assessment to novel HMT paradigms for eVTOLs in UAM operations.

Monitoring in novel HMTs. Monitoring is a crucial element of human-autonomy teaming in novel aviation operations. Across a distributed team of agents, cross-checking or monitoring is needed to identify safety-critical situations.

Prof. Pritchett's research group at Penn State used simulation to examine the impact on monitoring performance of both (a) varying information distributions across the team and (b) the timing of when monitoring occurs.

The researchers took a cookie-delivery concept of operation (ConOps) for an advanced aerial mobility (AAM) small UAS (sUAS) delivery operation and translated it into a computational model. They then further refined the ConOps through simulation utilizing the Work Models that Compute (WMC) framework (Ref. 26). Within a day's simulated operation involving several agents, 5 electric vehicles, and 30 missions totaling 60 flights, the case study introduced a degraded vehicle battery that would, if undetected, eventually result in the vehicle departing without sufficient energy to complete its flight. The work model was analyzed for work dynamics and to identify timing constraints and information requirements of the actions comprising the work. Additionally, the impact of function allocation on the team and task work dynamics was measured by the task load and information requirements on each agent as well as the overall completion time. Thirdly, the ability to generate monitoring actions during runtime based on mismatches between authority and responsibility in the function allocation allowed the analysis of the task load and information requirements of basic, full and extended forms of monitoring. The computational model and simulation enabled the analysis of the emergent system dynamics of a wide-range of HMT structures as represented by the number of agents, their assumed capability and task limits, and the allocation of authority and responsibility across the team.

Examining achievable true positive and false positive detection rates for each variation of monitoring, none of the types of monitoring were able to achieve perfect performance. Instead, monitoring accuracy in detecting a degraded battery varies significantly with the information distribution across the team and the timing of when the monitoring is conducted. Further, monitoring increases agent task load and the amount of information needing to be transferred between agents.

This work yielded four insights:

- *Coordinating taskwork.* Agents can control when they perform some of their tasks, but other actions are time-critical, and need to happen at specific times, requiring coordination. Agents must be able to communicate to coordinate, and agents must be able to interrupt current actions to perform time-critical actions.

- *Ensuring monitoring occurs.* Civil aviation CRM practice has evolved to overtly require monitoring that might be delayed or omitted under time pressure. There are immediate consequences of delaying taskwork, but if everything is going well, missed monitoring usually goes unnoticed. An analogous concept might be needed in new operations.

- *Monitoring and resources.* Monitoring requires effort and information. Systems must be designed to provide this information. When taskload increases, monitoring gets delayed beyond critical points (i.e., monitoring is missed/skipped). In current-day operations, CRM is a protection against this by overtly requiring monitoring.

- *Variable, imperfect monitoring accuracy.* There are theoretical obstacles to 'perfect' monitoring, such as taskload, timing, and the operational dynamics. The efficacy of monitoring will vary based on information distribution and on the criterion for measuring monitoring accuracy (e.g., comparing against an operational objective vs against an idealized process model).

Hazard analysis for novel HMTs. Prof. Fleming's research group at Iowa State adapted an existing hazard analysis technique to explore hazards for eVTOL aircraft in UAM operations. Their research, which falls under the label of "Safety-guided Model-based Design," seeks to answer two questions: (a) *What are the design errors that may escape a model-based verification program for safety assurance?* and (b) *How can we define a design model that is free from those design errors?* Their work leverages the rapid advancement of formal methods and Model-Based Safety Analysis (MBSA) in order to combine them to attempt to verify whether the safety-critical scenarios are adequately addressed by the design solution of a complex HMT system.

The Iowa State team's effort identified a key gap: if specific safety-critical scenarios are not included in the given design solution (i.e., the model) in the first place, the results of MBSA cannot be trusted for safety assurance. To tackle this problem, the Iowa State team developed a new safety-guided design methodology called System Theoretic Process Analysis Plus (STPA+) to complement MBSA. Inspired by STPA, STPA+ treats a system as a control structure. This is particularly well-suited to analyzing systems with complex interactions between humans, machines, and automation. Three methods are developed in STPA+ that tackle the possible omission of safety-critical scenarios caused by (1) incorrectly defined safety constraints, (2) improperly constrained process models, and (3) inadequately designed controllers. In this way, STPA+ attempts to derive an adequately defined design solution as the input to an MBSA verification program and bridge the gap between current MBSA approaches and safety assurance.

Assured Human Machine Interface for Increasingly Autonomous Systems (AHMIIAS)

The Collins Aerospace, Florida Institute of Technology, and Soar Technologies, Inc. performers developed a framework for (1) specifying the roles of a human operator and autonomous co-pilot, (2) verifying that the team satisfies safety properties, and (3) verifying that the autonomous co-pilot meets its requirements. One of the example systems used to evaluate the framework was enhanced with a learning function that learns the pilot preference for an early warning threshold for a potentially unreliable sensor, and each of the requirements was proved over the resulting system (Ref. 27).

Architectural frameworks for modeling and assessing HMTs. As increasingly autonomous systems take on more responsibility for safety critical decision making and the human–machine role allocation changes, new failure modes may arise. With the increasing complexity and autonomy in these HMT paradigms, traditional verification approaches such as testing will not suffice. The AHMIIAS research focused on creating an environment in which the researchers could (1) identify requirements and procedures for safe HMT behaviors; (2) include the human in the model so that human–machine interactions can be analyzed; (3) use formal methods where possible and practical to prove safety requirements are satisfied by (the model of) the system or component; and (4) to evaluate the impact of component faults on the human–machine interactions. The performers used the Assume Guarantee Reasoning Environment (AGREE) (Ref. 28), an annex to the Architecture Analysis and Design Language (AADL) (Ref. 29) to capture formalized requirements for selected eVTOL IFCS concept examples. They also used AADL and AGREE to create a system architecture model with requirements allocated to components to show that the system requirements are satisfied given the component requirements. Behavioral analysis in the presence of faults was performed using the AADL safety annex described in (Ref. 30). To show that the system requirements are satisfied by the implementation in Soar, the cognitive architecture framework used to specify learning agents, the performers translated the Soar implementation into the formal model checking environment nuXmv, and then used the nuXmv model checker to verify select safety properties.

This architectural framework provided a centralized repository for requirements, constraints, assumptions, and models that were used throughout the design, development, and safety assessment process for the selected examples. This enabled the performers to manage change rigorously and catch conflicting assumptions as refinements to the roles and responsibilities in the HMT were made. This also allowed for "what if" scenarios to be run to examine the implications of making a change to the HMT paradigm (in terms of roles and responsibilities) and allowed teams of interdisciplinary experts (e.g., requirements engineers, cognitive architecture designers, formal methodists, etc.) to exchange information in a common framework. This enabled early consideration of the downstream effects of design decisions, including the difficulties that they might cause for the ensuing safety assessment.

Learning components in HMT paradigms. Integrating a learning subsystem with an existing decision-making agent to create "learning in decision making" is a non-trivial task, even before safety is concerned. The AHMIIAS researchers attempted to use reinforcement learning (RL) to train a Soar cognitive agent to learn a pilot's preferences for receiving alerts related to positioning error during an eVTOL landing. Signals for error between the GPS, LIDAR, and IMU sensors were examined. Soar cognitive agents allow for preferences to be learned for proposed rules; however this required extra memory for the agent to store data, since RL requires several cycles to process and finalize the computation. Similarly, methods for initializing the threshold values for the rules learned needed to be incorporated into the architecture. Several learning policies associated with RL were evaluated (i.e., Boltzmann with high temperature, Boltzmann with low temperature, simulated annealing decreasing temperature, and Softmax). The policies changed the value of the reward based on the algorithm specific to that policy. The positive or negative value of a reward was based on the input received from the pilot. One of the key challenges was how to know when to stop learning. This problem was solved heuristically by executing 50 trials and observing the preference values of preferred actions. The rule for generating an alert stabilized around 1.70 and the rule about when not to alert stabilized to a value of -1.60, after about 35 trials, as the agent was trained using the scripted pilot response. This stabilization technique is sensitive to the initial values selected, and different heuristics may result in agents trained to different final thresholds. Such sensitivities indicate that termination of training is more an art than a science.

In the integrated learning agent, the user's error-alert preferences and responses were incorporated into the larger chain of decision-making to determine when to disable a sensor that appeared to be dysfunctional. The performers found that more contextualized learning enabled better results in terms of false alarms. They discovered that it was important to make sure that learned preferences for different error signals did not interfere with each other (allowing the system to learn different preferences for different error types). They also found that false alarms were reduced if the learning "decision space" allowed the system to learn different preferences and error tolerances for different mission phases.

Modeling and Analysis of Safety in New Human–Automation Teaming

The MIT research had two goals: (1) develop a framework based on systems theory for creating safe and effective teaming in IA systems in UAM operations and (2) develop and assess a novel new paradigm for the use of top-down modeling and analysis to assure safety, security, and other system-level properties in the conceptual development of a UAM operation. The performers investigated UAM concepts that incorporate complex teaming and coordination among humans and automation using a System-Theoretic Process Analysis (STPA). The STPA hazard analysis is used to identify potential scenarios that could lead to future accidents. First, the MIT team introduced a novel system-theoretic analytical process to identify unsafe collaborative control actions (Ref. 31). Second, they extended an existing hazard analysis technique to explore the hazards that a human–machine team might create.

Complex collaborative control in novel HMT paradigms. Human teams collaborate by establishing roles, changing functional authorities, maintaining team cognition, coordinating, and helping one another close control loops. These complex interactions are inspiring novel system concepts to improve human–machine and multi-machine collaboration. However, these new systems challenge existing methods to model, analyze, design, and assure their safety. As such, few have been fielded in safety-critical domains like aerospace.

Research conducted in (Ref. 31) introduces a system-theoretic framework to describe multi-controller interactions. This includes a taxonomy of seven structural dimensions that influence such interactions and nine dynamics observed in collaborative control; they frequently arise in UAM operations under the range of industry proposed eVTOL IFCSs.

An analyzed set of controller interactions in aerospace systems demonstrates the framework and highlights how designers are trying to create more sophisticated systems. Seven classes were identified in a taxonomy describing the structure of interaction between controllers (i.e., types of controllers, hierarchical structure, behavioral intent, connectivity, information exchange, roles and responsibilities, and developmental origins). These seven classes were coupled with the nine identified collaborative control dynamics (i.e., cognitive alignment, lateral coordination, mutually closing control loops, shared authority, transfer of authority, dynamic authority, dynamic hierarchy, dynamic membership, and dynamic connectivity) to evaluate a set of 101 component interactions that are part of aerospace systems. The 101 evaluated systems represented both fielded systems and unfielded systems, e.g., systems in concept development, systems that have been prototyped but not yet fielded, etc. Most of the systems were encountered by the MIT team while reviewing the teaming literature, and the set is not necessarily representative of all possible and actual aerospace systems. However, there are two important takeaways from this analysis. First, there is evidence in the literature that systems are being designed to exhibit each of these complex collaborative control dynamics. And second, of the systems analyzed, those that have not yet been fielded tend to exhibit more of these complex interactions. These points support the argument that causal factors associated with these dynamics must be considered in safety analysis and design. Thus, acceptable means of considering these dynamics need to be established before the proposed aircraft and operations that embody them are fielded.

Systematic approaches to analyze safety. A rigorous and systematic approach to analyze safety and enable the safety-guided design of systems that exhibit collaborative control is required to enable systems with complex, collaborative control paradigms. The system-theoretic taxonomy developed by MIT consists of (1) a taxonomy of the structure of interactions between multiple controllers and (2) a set of dynamics observed in collaborative control. It creates the necessary foundation to extend STPA methods needed to systematically identify causal factors associated with these interactions. Researchers at MIT have begun developing such a process as follows. First, a mechanism is developed to incorporate the nine collaborative control dynamics into STPA control structure models so that they are explicitly considered in hazard analysis. Second, a process is derived from STPA to identify unsafe combinations of control actions between multiple controllers. The procedure systematically considers potential issues involving gaps, overlaps, transfers, and mismatches in authority that are found in teams. It is executed using an abstraction-based algorithm that manages combinatorial complexity and provides automation support. Third, a method is introduced to identify causal factors from these unsafe control combinations that relate to the collaborative dynamics. This extension to STPA is referred to as STPA-Teaming.

The STPA-Teaming extension was used (Ref. 32) to analyze several crewed-uncrewed teaming applications that focused on the collaborative interactions between the human pilot and the UAS in the execution of shared mission tasks. This research employed both scoping and abstraction to enumerate, refine, prune, and prioritize the sets of collaborative commands that together can lead the system to enter a hazardous state. The ability to find unsafe combinations of control actions can then be aligned to one (or more) of the nine collaborative control dynamics outlined in the taxonomy. As a result, new causal factors can be found that were previously not systematically considered, as the refinement of the nine factors would expose unsafe control combinations that would have been abstracted away. Currently, heuristics can be used to expose novel causal scenarios, but the researchers have noted that a template for a generic collaborative control structure which is able to express these causal relationships explicitly in the system model would greatly enhance the user's ability to derive such scenarios.

Other NASA research

NASA participates in other research that bears on the issues we've raised in this paper. One strand of this research includes remote piloting and other diverse piloting paradigms, including m:N operations. Another concerns pilots' ability to intervene to prevent an accident under novel HMT paradigms.

Remote piloting and other diverse piloting paradigms. With the advent of autonomous and uncrewed operations, diverse piloting paradigms have emerged. Small UAS vehicles are either remotely piloted or are potentially autonomous. For the remote piloting of these vehicles, m operators might have responsibility for N vehicles. Given that the transition from 1:1 to m:N inherently changes the role of the human operator and shifts much of their traditional tasking and execution to the supporting systems, the technologies that advance the capabilities, robustness, and resiliency of automation and autonomy are critical for the ability to conduct the envisioned operations safely and dynamically.

For m:N operations to occur in a safe and viable manner, a few key considerations must be addressed. Firstly, the human role and their interaction with the system of aircraft must be understood and designed for. Secondly, the implications of current policy and regulation on the feasibility of such operations must be properly comprehended. The current approval efforts with small UAS and beyond-visual-line-of-sight (BVLOS) operations provide a potential blueprint for the path that lays ahead (Ref. 33). Finally, an ability to apply performance- and risk-based criteria to system approvals at the multi-aircraft systems level could provide a more holistic understanding of the *m*:*N* operational landscape.

If the deployment of sUAS are seen as a roadmap to the potential adoption of *m*:*N* HMT paradigms, then it is important to assess the current limitations and assumptions inherent in such operations today. Non-recreational operations of sUAS encompass various activities such as property photography, roof inspections, and aiding nonprofit organizations. Such operations are governed by regulations specified in 14 CFR Part 107, commonly known as the Small UAS Rule. However, waivers may be sought for operations contrary to Part 107 regulations, subject to FAA approval.

Data integration and visualization methodologies must ensure that operators are able to maintain appropriate levels of situational awareness for all assigned vehicles without negative effects on their workload. To accomplish this, interfaces must provide human operators with enough information and stimulation to understand the status of their vehicles and avoid underload states that may lead to slow response times, but not so much as to overload users and reduce performance (Ref. 34). Furthermore, *m*:*N* operations require careful coordination across teams of human operators. Technologies for all teams should be developed to support effective communications, shared situation awareness, and efficient task sharing among the team. Communication between teammates can either be voice-based or text-based, but the approach should ensure compatibility with other task demands (Ref. 35). Individuals within a team should be provided with synchronized access to the same data sources (Ref. 36) and be able to share tasks among members.

Ultimately, gaining approval for novel concepts like *m*:*N* operations that inherently have elements inconsistent with existing regulations and their underlying motivations and assumptions will likely require significant regulatory expertise and time, in along with technical innovation, to gain the needed accommodations and approvals. It may be necessary to progress through a series of operations with increasing levels of complexity and potential risk to help motivate and inform the development and implementation of regulatory changes and supporting policies. A key observation is that approval for *m*:*N* operations with lower inherent risk will be easier to obtain, indeed they are already being obtained for sUAS operations conducted under Part 107, albeit still under case-by-case review and waiver issued by the FAA rather than following requirements prescribed directly in the regulations. Approval of more advanced *m*:*N* operations will likely follow a progression of operations with progressively higher levels of complexity and potential risk that support CAAs in the development of appropriate confidence in the enabling technologies, as well as inform the development of regulatory updates recognizing the role and requirements of these technologies.

Pilot's ability to intervene. The pilot's ability to intervene in some proposed HMT paradigms will be severely limited in comparison to current piloting. For instance, if the flight controls system overseeing the inner loop rotor control of an eVTOL octocopter experiences a catastrophic fault, it is unclear what, if anything, a pilot may be able to do to recover the vehicle. Additionally, the response time of the pilot should be taken into account for any action proposed as a crew mitigation in an Functional Hazard Analysis (FHA). If there is insufficient time for the pilot to respond, or if the pilot cannot maintain sufficient situation awareness to respond, or if the pilot's skills have degraded to the extent that the response is no longer tenable, it may not be viable to have the pilot mitigate the fault condition.

It is impossible to anticipate every future possibility. Out of necessity, resilient humans are relied upon to deal with unforeseen, unplanned, and unanticipated hazards and circumstances. No one has yet found a way to guarantee absence of unpleasant surprises in fielding novel human–machine teaming paradigms with new airborne capabilities, and for some HMT paradigms, the likelihood of unpleasant surprises is high. Pilots will thus need to have sufficient situation awareness, time to respond, and the skill needed to intervene.

DISCUSSION

It is premature to be able to say that the path to increasingly autonomous aviation has been charted out. Fundamental questions remain regarding whether the goal of such an endeavor should be to find the most beneficial human-machine allocation of functions that enhances safety and resilience or whether the end state of full autonomy is a presupposition of such a path. Based on the desired endgame, the relevant research questions will differ, as the readiness of technological solutions to assume responsibility for the safety of flight in complex, uncertain scenarios in an open world will need to be addressed fully.

HMT will be fundamental to future aircraft design, as one cannot even begin the safety assessment of an aircraft without first knowing its functions, which depend on whether, and in which form, parts of it will team with a human pilot or operator. Research like that discussed above has significantly added to the body of work surrounding HMT. Significant results include discovering how the use of monitoring in HMTs can foster safety-producing behavior when the monitoring is constructed in ways to enhance HMT performance. For instance, the efficiency of monitoring varies based on how information is distributed across agents in the team and on whether the criterion for measuring monitoring accuracy is based against an operational objective or against an idealized process model. Similarly, it was discovered that learning-enabled components performed better when they were contextualized, that is, when the learning-enabled component was allowed to learn different preferences for different error types in different phases of flight (which did not interfere with one another), the false alarm rate for alerting to an error threshold went down significantly. Additionally, a taxonomy of the structure of interactions between multiple controllers was developed, and a set of dynamics observed in collaborative control was documented. This documentation of collaborative control patterns enabled analysts to find unsafe combinations of control actions in a systematic fashion, thereby exposing causal factors of hazards that may have been otherwise overlooked. This type of research is necessary in order to assemble the body of knowledge that will be required to field novel HMTs, as it will provide a solid foundation for any safety assessment that will occur around these systems.

In our focus on HMT, however, we have left important matters by the wayside. For example, artificial intelligence (AI) and machine learning (ML) might feature in implementations and raise important questions: *How do we know that the AI system behaves as its designers and the safety assessment team intend it to? How do we know what unintended behavior the AI system might exhibit? How do we know the safety implications of that unintended behavior? What kind of monitoring will be needed for forensic analysis of these systems after an accident or incident?* As the FAA has observed (Ref. 37), these questions highlight the need for research.

Similarly, there are questions related to the sensitivity and fragility of AI or ML components trained on limited sets of data that may not cover the entire operational design domain of the system. Since ML techniques are sensitive to initial parameter selection and termination of training is more an art than a science, the reproducibility and explainability of such components may create a great deal of difficulty as they are integrated into HMTs. Additionally, if these AI or ML components are used outside of their training domain or in different contexts (e.g., users who have different thresholds for alerting, different phases of flight, etc.) the results can be such that the component no longer meets its specification. This will create enormous issues in HMT paradigms where the human is subject to decisions that are opaque and unexplained.

There are many other issues out of this paper's scope, including ethics, economics, governance, and non-civil aviation platforms. We recognize that these issues inform and influence the civil aviation HMT ecosystem.

CONCLUSIONS

Novel human machine teaming paradigms in eVTOL aircraft under UAM operations raise questions about how safety and safety-producing behaviors are designed, developed, evinced, and assessed in the U.S. national airspace system and abroad. The advent of increasingly autonomous systems into safety critical decision-making—in piloting, air traffic control, or other aspects of aircraft or airspace design, operation, management, maintenance, and retirement—will act to disrupt the conventional means by which safety is assessed and assured. Specifically, it is unclear in these novel role and responsibility allocations how safety producing behaviors are generated for these complex, interconnected systems.

No design assurance process will ever identify *all* the hazards in any complex unbounded dynamic system. There will *always* be hazards that are unforeseen or unanticipated. Because the existence of these hazards, which can be referred to as "predictably unavoidable" (Ref. 38), is known *a priori*, planning should occur to mitigate the situations when those hazards inevitably evince themselves. Currently, our safety processes for the management of these "unknown unknowns" include preparing for and recovering from the resulting failures—that ensue from these "unknown unknown" hazards manifesting themselves. Humans currently represent the primary source of preparation for and recovery from—and prevention of—hazards that are unanticipated during design.

Additionally, early enthusiasm for the adoption of novel, rapidly evolving technologies and innovative role and responsibility allocations between humans and machines may lead to an overestimation of their potential benefits without a due consideration of their attendant costs, such as time, money, and most importantly, unintended consequences to this or other interrelated systems. Several fundamental questions must be answered before novel human–machine paradigms—which may be enabled by emerging technologies such as machine learning for increasingly autonomous systems—can be fielded in safety-critical aviation contexts.

It is important to be able to clearly characterize the nature of the human–machine interaction paradigm being advocated for in the implementation of a given function or task. Without this, it will be impossible to specify the required behaviors that will be necessary to produce the requisite properties (i.e., safety, security, availability, etc.). Additionally, it is critical that the behaviors of the novel human–machine paradigm required for the allotted task or function be predictable. It is very easy to allocate all the tasks that machines are good at performing to that component, thereby leaving the human without the necessary situational awareness to perform their tasks or intervene when required. This form of human–machine interaction sets the human up for failure, and will degrade the safety of the system. Fundamental research is required on how human–machine teaming paradigms are characterized, implemented, and evaluated, with respect to internal agent performance and overall emergent properties. It is important to note that these frameworks for characterizing, implementing, and evaluating human–machine interactions should be a methodical and reproducible analysis.

The ability to characterize the human contribution to safety is a key topic of research that must be addressed before current human–machine paradigms can be altered, as otherwise there is no way to predict the effect of the paradigm change on the safety of the system as a whole. Similarly, it is critical that a systematic and repeatable way be developed to explore, characterize, allocate, and assess potential functional allocations in human–machine teaming paradigms, thereby allowing rational documentation of any tradeoffs to be made. This research has been deemed to be a "whole of community" effort, engaging academia, industry, and relevant government agencies.

Any novel paradigm for human–machine interaction or teaming crosses a boundary in knowledge between that which is known (and potentially well understood) to that which is likely unknown. This will rapidly lead to encounters with the unforeseen and the unexpected. Even incremental changes to a traditional human–machine teaming paradigm—by deployment in an novel environment or in an emerging operation; or through use of a new technology (e.g., AI/ML) or design—may cause a fundamental change in the knowledge required to design, operate, maintain, and decommission those systems safely. New hazards may emerge, and old hazards may gain new prominence or paths to realization: gaps in knowledge may be impossible to detect until the system has been in service for an extended period of time. Due to the multidisciplinary nature of human–machine teaming and the potentially shifting locus of control for the making of safety critical decisions, it is vital that interdisciplinary teams of experts across IA systems, human behavior, data sciences and others, be formed to design, develop, deploy, assess, and perform research on systems with novel human–machine teaming paradigms. After all, it may not be readily apparent what is relevant to test or monitor until a new safety concern emerges.

But even the most well-thought-through research will fail to ask *all* the right questions. The deployment of eVTOL aircraft in UAM operations employing novel human–machine teaming concepts will encounter hazards, or reveal contributions to hazards, that no one thought of, much less took as seriously as reality warrants. Edge cases and unknown unknowns are a fact of life. Responsible deployment thus both balances the resulting unknown risk and monitors carefully for signs of trouble before these result in accidents or serious incidents. Deployment should prioritize situations where the potential benefits for those who might be put at this unknown risk benefit substantially from taking it. A staged deployment in progressively more risk-tolerant public-good operations—e.g., wildland firefighting, hurricane relief and recovery, etc.—will enable initial operations with novel HMT paradigms in a viable manner. And the data collection and analysis that surrounds these eVTOL aircraft undergoing these novel air mobility operations in progressively more risk-tolerant environments should be planned so as, to the extent practicable, to detect potential issues before they manifest in losses or even near misses. While it is impossible to deploy novel HMT paradigms with IAS without increasing risk, it is important not to damage paths to transition for novel HMT and IAS.

Finally, it is critical to note that the capture of the fundamental research results and insights in a body of standards is crucial to the enabling of novel human machine paradigms in safety critical systems. However, it is impossible to create standards before the fundamental research is performed and that knowledge is gained, as there will remain a great uncertainty surrounding what knowledge will need to be codified.

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