Work-in-progress: Extending Uncertainty Frameworks for Aviation Safety Analysis

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Abstract

Uncertainty, whether related to knowledge, task demands, or social roles, is a critical factor in both learning and decision-making. It can stem from ambiguity during human-human or human-machine interaction. Uncertainty is a feeling of doubt, confusion, or wonderment about the ambiguous situation and can arise due to inadequate training, lack of information, and poor communication. Suboptimal management of uncertainty can pose serious safety risks in critical aviation scenarios, especially involving student pilots, characterized by ineffective information exchange between student pilot and instructor pilot. While prior research has investigated how such uncertainties are handled in high-risk scenarios, especially focusing on Crew Resource Management, these have not translated into education focused on helping student pilots handle uncertainty productively to mitigate safety risks. To address this gap, we draw on emerging research in engineering education, investigating how students collaboratively manage uncertainties productively. This paper introduces a conceptual framework that bridges educational theory and aviation human factors to explore how uncertainty influences pilot learning, communication, and decision-making. The framework combines epistemological uncertainty (knowledge- or skill-related) and positional uncertainty (role- and authority-related) with the Human Factors Analysis and Classification (HFACS) framework to identify underlying contributors to uncertainty in flight training. Drawing parallels between collaborative classroom problem-solving and instructor-led flight training, we examine student and instructor pilots' experiences of uncertainty during training sessions. Using a qualitative thematic approach, we analyzed thirteen narrative reports from NASA's Aviation Safety Reporting System (ASRS) involving student-instructor training flights. Findings indicate that both epistemological and positional uncertainties were involved, and they are most frequently associated with skill-based errors within the HFACS classification. These insights may help inform improvements in flight training design, simulator-based interventions, and aerospace engineering curriculum development.

Keywords

uncertainty; engineering education; aviation human factors; safety analysis; training

Introduction

Uncertainty in the context of learning and making decisions has been previously investigated in the context of engineering education (e.g., [1], [2], [3]). It refers to doubt or lack of clarity about a situation, whether related to one's knowledge, the task at hand, or interactions with others [1]. If it is not managed well, it can hinder learning and performance by undermining students' self-confidence and decision-making abilities [4]. In collaborative settings, managing uncertainty requires coordinating with peers and navigating social dynamics [2]. In multi-crew flight environments, uncertainties may emerge in coordination tasks between the captain and the first officer. Even among highly experienced professionals, differences in how individuals interpret and understand knowledge can lead to varied interpretations of ambiguous information, which can challenge cockpit decision-making [5]. Social dynamics such as hierarchy and varied leadership styles can suppress (co)pilot input, leading to missed error detection or unchallenged decisions [6]. Prior research into effective crew resource management (CRM) strategies highlight potential means for negotiating and resolving uncertainty collaboratively to maintain safe flight operations (e.g., [7], [8]). Further, transparency of information, especially the representation of uncertainty (or confidence), improved human performance [9]. However, it is unclear how these factors translate to training scenarios involving smaller aircraft, such as single engine training aircraft (e.g., Cessna 172), novice situational awareness, and skewed teacher-student dynamics.

Flight training sessions represent parallel high-stakes contexts where uncertainty plays a critical role. Similar to a collaborative learning environment, instructors or certified flight instructors (CFIs) and student pilots work together to ensure safe flying conditions by continuously exchanging information, feedback, and transfer of control. Student pilots are likely to encounter unexpected scenarios and ambiguous instructions, and they must manage them collaboratively with flight instructors. For example, a study highlighted that mismatches in instructor–student personality types can contribute to increased uncertainty and cognitive strain during flight training, potentially undermining learning and performance [10]. NASA's Aviation Safety Reporting System (ASRS) includes numerous incidents involving training-related uncertainties connected with communication breakdowns and lack of role clarity [11]. A survey of pilots who survived inflight loss of control incidents revealed that about one-quarter mentioned inadequate training or improper supervision as contributing factors to their incidents [12], [13].

In this study, we build on previous research [14] and elaborate on the role played by human-factors dimension in uncertainty and its management. Our goal, in this paper, is to present a novel conceptual framework and operationalize it to identify the types of uncertainties that contribute to aviation incidents and various human-factors involved. This framework contributes not only to aviation safety research but also to aerospace education by informing curriculum design and instructor training approaches. Specifically, the framework can guide the development of flight simulator-based training programs that prepare student pilots to manage uncertainty productively in high-risk scenarios. Additionally, the framework can be integrated into instructional flights to highlight how uncertainty in the cockpit may lead to near-miss events, serving as structured learning opportunities for student pilots and precautionary guidance for certified flight instructors (CFI). Apart from operational training, this research can support the inclusion of curriculum modules within aerospace systems engineering and safety courses, focusing on human-system integration, hazard analysis, and risk-informed design. As an exploratory study, this paper focuses on conceptual framework development and qualitative insights rather than statistical inference.

Conceptual Framework

We extend the framework of uncertainty in the educational context [2] to aviation training scenarios. Since uncertainty is a subjective experience, it is essential to understand how it is framed or constructed by individuals within a group. Based on prior research [2], we consider two types of framing uncertainty– epistemological and positional. Epistemological refers to how individuals interpret what kind of knowledge or skill is relevant to make sense of a situation (e.g., "What do I need to know to understand ambiguous ATC instructions?"). Positional refers to how individuals view their role and the roles of others in a social or collaborative context (e.g., "Is it my responsibility to act now, or should I defer to my co-pilot?"). These categories are illustrated in Fig. 1, which maps how epistemological and positional uncertainty manifest in both classroom and cockpit learning environments.

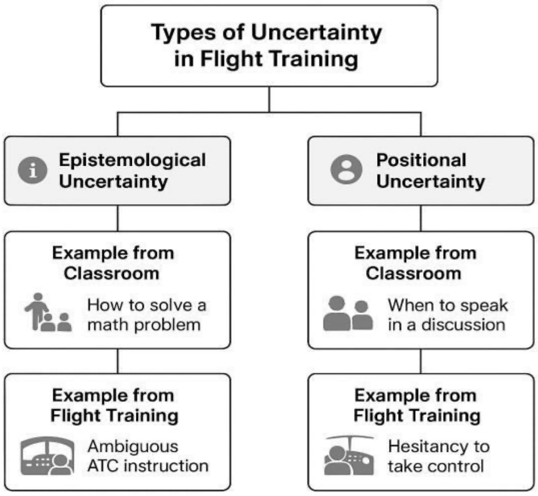

Fig. 1. Conceptual categories of uncertainty as applied to both classroom and flight training contexts.

In addition, we utilize the Human-Factors Analysis and Classification System (HFACS) [15] to understand the potential mechanisms underlying these uncertainties (Fig. 2). HFACS categorizes human contributions to error into four hierarchical levels: Organizational Influences, Unsafe Supervision, Preconditions for Unsafe Acts, and Unsafe Acts. HFACS has since been widely applied across aviation, maritime, healthcare, and other high-risk domains, demonstrating its effectiveness in identifying recurring human and system-level vulnerabilities and supporting the development of targeted safety interventions [15], [16]. As this research focuses specifically on cockpit-level interactions between student pilots and instructors, Organizational Influences are not directly observable in our dataset although it plays a crucial role in shaping uncertainties. Therefore, the exclusion of organizational influences level in this study reflects the methodological scope of the study, rather than a limitation of HFACS. This hierarchical classification enables a clearer identification of the sources of uncertainty within the cockpit during instructional flights.

Relevance of Uncertainty Framework in Aviation Training Contexts

Mismanaged uncertainty in flight settings can lead to significant safety risks, including incidents or accidents. Pilot error is a major contributor to around 70% of all aviation accidents, many of which could be mitigated if the pilots had better judgment, knowledge of aircraft systems, and a better understanding of weather patterns and general aircraft procedures, essentially, if they had been better equipped to manage these uncertainties [17] – [19]. Mismanaged uncertainty may be found in the instructor–student relationship during flight training. Much like instructors in classroom group projects, flight instructors must determine optimal moments to intervene or allow student pilots to learn from experiences. In parallel, students must gauge when to seek assistance or take initiative, actively negotiating with authority gradients. Misalignments in these negotiations can lead to serious safety consequences. For instance, aviation safety reports highlight incidents where delayed instructor intervention during unstable approaches led to near accidents [11]. Conversely, student pilots' overreliance on instructors has contributed to procedural oversights and near-misses, demonstrating clear intersections between epistemological uncertainty (lack of procedural knowledge) and positional uncertainty (authority dynamics) [11].

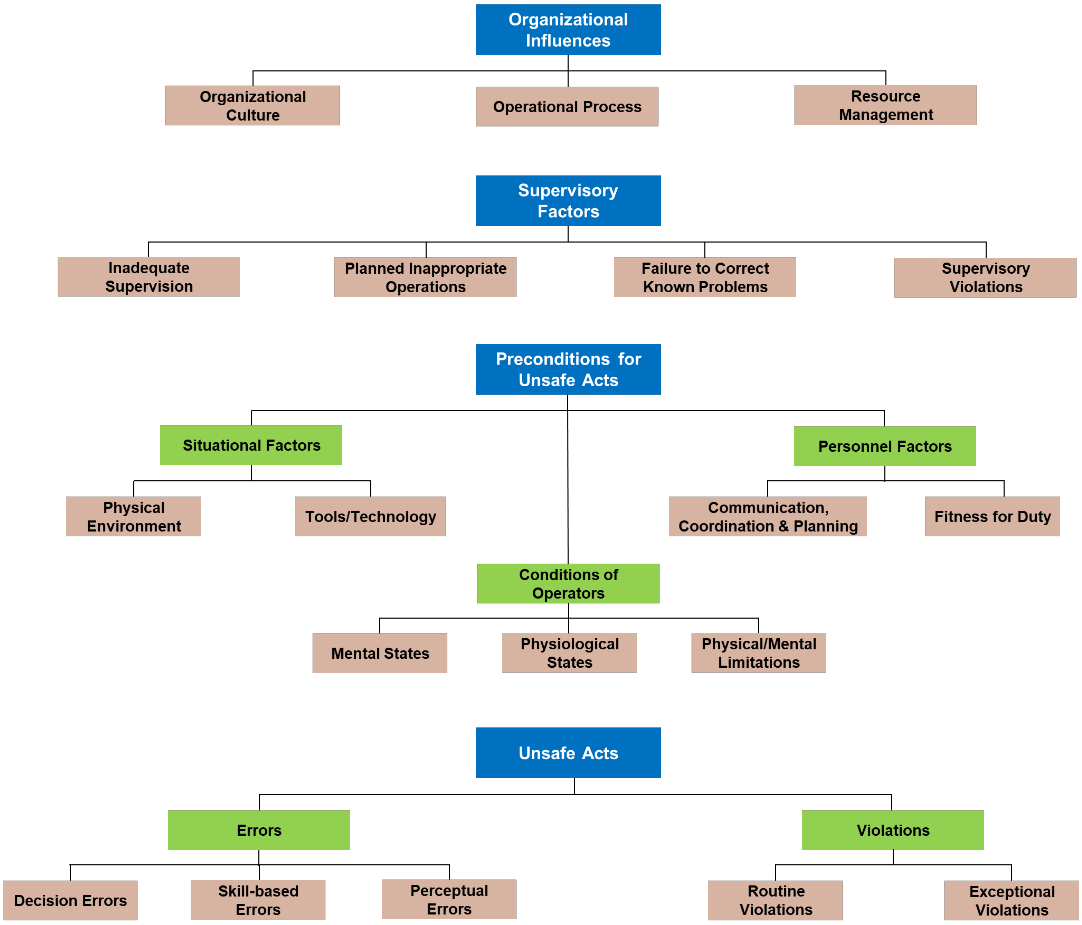

Fig. 2. Human-Factors Analysis and Classification System (Adapted from: https://www.hfacs.com/hfacs-framework.html)

Methodology

The NASA Aviation Safety Reporting System (ASRS) is a rich source of qualitative data on operational incidents and human factors issues in aviation [20]. We searched this database using specific linguistic markers associated with expressing uncertainty - modal verbs (“might”, “may”, “maybe,” and “perhaps”), hedging expressions (“I suppose”, “It seems”, “I doubt”, “I guess”, “It appears”, “I think”, “I assume”, “I suspect”, “It is possible that”, “It is likely/unlikely that,” and “I guess”), adverbs (“possibly”, “probably”, “likely”, “unlikely”, “presumably,” and “arguably”), and self-reports (“I am not sure”, “I am confused,” and “I would not know”). We focused on incident reports logged between January 2024 – January 2025 to identify recent episodes. We narrowed our search to flight mission (training) to select incidents related to training flights and Federal Aviation Regulations (FAR) Part 91 in alignment with the motivation for this study. Herein, FAR Part 91 covers the rules for general aviation operations in the U.S., applying broadly to private, corporate, and non-commercial flights, outlining pilot responsibilities, aircraft requirements, maintenance, and airspace rules to ensure safe operations [21]. Using these search criteria, we extracted 373 incident reports. From these, we further refined the dataset to thirteen reports involving a student and instructor in the cockpit where both have logged their perspectives for the same incident. This approach aligns with our focus on student-instructor dynamics, and dual perspectives enable deeper qualitative analysis. Although this dataset does not allow for broad statistical inference, it provides a strong basis for conceptual framework development.

Using qualitative thematic analysis [22], we identified moments of confusion, hesitation, or disagreement between student pilots (SP) and CFIs, reflecting underlying issues of knowledge gaps (epistemological uncertainty) and authority dynamics (positional uncertainty). Additionally, another qualitative content analysis was conducted, and the selected cases were systematically coded and categorized using the HFACS framework. These uncertainties are not mutually exclusive and thus the same incident may reflect both uncertainties. To ensure reliability and validity of this process, one of the authors who is an expert in uncertainty research first coded five data records. All the authors then discussed these codes and corresponding justification to verify the relevance of these codes. The student author was then trained on these data records. He then coded the rest of the dataset which was subsequently reviewed by the expert for any inconsistency or bias. The excerpt below provides an example of our qualitative coding. Due to space constraints, we present the relevant parts from the narratives with key phrases highlighted in bold.

> ACN (Incident ID): 2198951
> Narrative 1 (Student Pilot-SP): *This was during a PPL lesson with my CFI. We were cleared for take off from ZZZ Tower departing run heading. There were wind and gust conditions. I had my ailerons turned in to the crosswind with some rudder. I pushed full throttle as we started down the runway. Close to 55 kts I began to rotate up to takeoff. We skid a little right.* ***As a student pilot I panicked a little and over corrected with too much left rudder. My CFI and I think that gust played a factor but it happened quickly…I have never had an issues with take offs before and was unsure as to what was happening****… I do not remember* ***or believe that any wheels touched the grass but once we had started our ascent****… I am grateful for my CFIs quick thinking and ability to correct course and prevent a worse outcome.*
>
> Narrative 2 (Certified Flight Instructor-CFI): *…While taxiing, I briefed student on crosswind takeoff techniques. The student told me he was familiar with crosswind takeoffs as he had done them previously with his primary instructor… At approximately 50 knots he overcompensated for drift with a large amount of left rudder. The aircraft turned quickly to the left and began deviating towards the runway edge.* ***I quickly added rudder inputs to stop the left drift while simultaneously announcing 'I have flight controls'. Student immediately took his feet and hands off the controls****… At approximately 3000 feet and level in cruise, I transferred the controls back to the student. After a short discussion, I determined it was best to turn back to ZZZ to discontinue the lesson and de-brief what had transpired…* ***To prevent re occurrence, I would have monitored the student more closely****.*

This incident was coded as skill-based error (based on HFACS framework), reflecting the reporting of over correction of the left rudder. Furthermore, this incident had both epistemological and positional framing of uncertainty. Epistemological uncertainty was linked to the lack of proper knowledge and skill regarding how much rudder correction was needed. Positive positional framing of uncertainty was reflected by SP acknowledging their mistake and appreciating CFI's handling of the situation.

Findings

The narratives from both CFIs and SPs were influential in determining the uncertainty framing and HFACS classification. In the dataset, among 13 reports of uncertainty related incidents, we observed that positional framing appears in a smaller subset of reports (7 reports), indicating fewer reports in which responsibility or failure is attributed within defined roles or system positions (Fig. 3). Such framing can shape safety learning by directing attention toward improving knowledge and handling of social situations. In contrast, epistemological framing dominates, suggesting that most incidents are discussed in terms of how knowledge, understanding, uncertainty, or judgment contributed to the outcome. In the data, all 13 of the cases that were studied in this research had shown epistemological uncertainty. Epistemological framing is observed in all 13 cases, whereas positional framing was identified in 7 of the 13 cases. Furthermore, most of the incidents involved skill-based errors (7 cases).

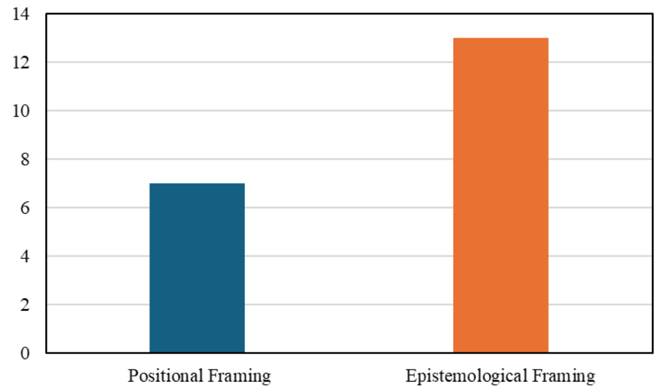

Fig. 3. Distribution of incidents by type of uncertainty framing (positional and epistemological).

The classification of 13 incidents as per the HFACS framework is presented below (Fig. 4).

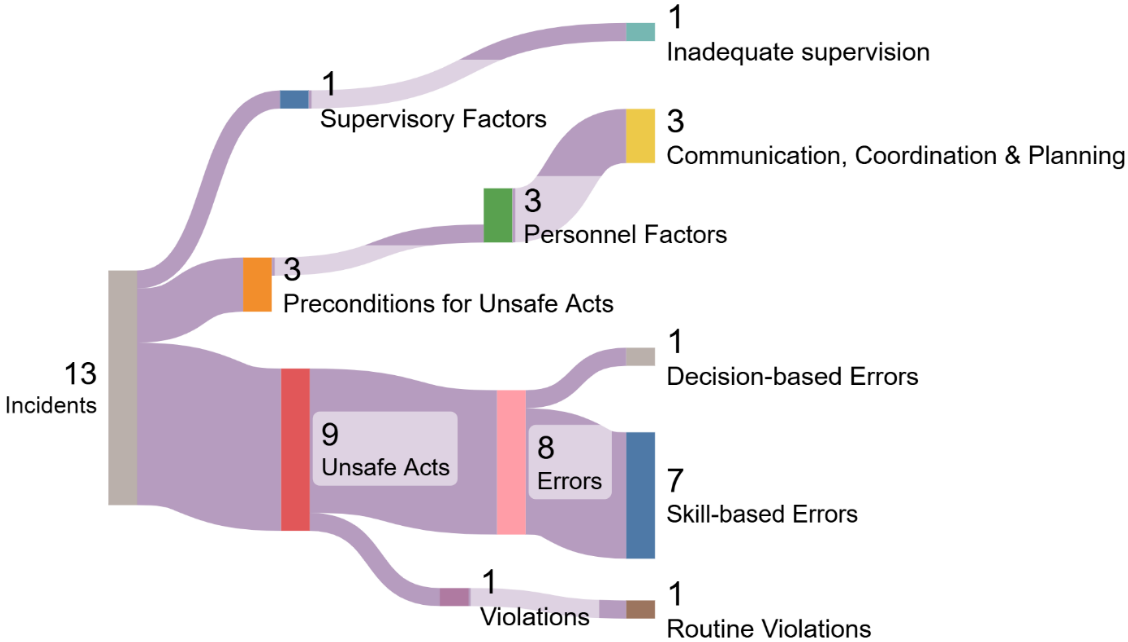

Fig. 4. Distribution of contributing factors classified using the Human Factors Analysis and Classification System (HFACS) framework.

We present excerpts from representative incident reports showcasing different types of HFACS and uncertainty framing between instructors and student pilots during these incidents.

Table 1. Representative incident reports from ASRS database with thematic codes

ACN (Incident ID)	HFACS + Uncertainty	Narratives
2094378	Routine violations + Epistemological framing	CFI: … *I noticed (due to strobe lights and beacons) a Cessna enter the runway and stop on the threshold markings (bars). Because I have seen this happen before, cleared to take off 'expedite' while an aircraft is on final, I continued.*

ACN (Incident ID)	HFACS + Uncertainty	Narratives
		Then I noted after 2 seconds this plane was not moving. There was so much radio traffic that I could not verify their intentions or my instructions…. SP: *... when given the instruction to 'hold short Runway XXL' which I had mistaken for a 'line-up and wait' instruction… While I was holding short on the runway, as I thought I was supposed to do, there was an aircraft I saw on ADSB on final, behind my aircraft…*
2203426	Decision-based error + Epistemological framing	SP: *... About 30-40nm out from ZZZ we determined the tanks were even and the pilot flying switched the tanks to both. At this point it is night and completely dark in the cockpit, except for the instrument panel. This is where the mistake was made and the pilot flying accidentally switched the fuel selector to off, but we didn't realize at the time. We should have verified…. we immediately applied full rich mixture and carb heat, but to no avail… I immediately noticed our very stupid mistake on the runway… I assumed we badly mismanaged our fuel supply and maybe had faulty fuel gauges and ran out, but if either of us checked the fuel selector we likely could have restarted the aircraft in the air…* CFI: *…When the fuel selector was getting switched back to both, it was accidently switched to the off position was it not noticed until after we had safely landed down at ZZZ4….*
2094378	Miscommunication + Epistemological & Positional framing	CFI: *... Then I noted after 2 seconds this plane was not moving. There was so much radio traffic that I could not verify their intentions or my instructions. I took the plane from my student and sidestepped to the left and started the go around procedure. The Tower then cleared that plane to take off and also contacted me asking my intentions…* SP: *…While I was holding short on the runway, as I thought I was supposed to do, there was an aircraft I saw on ADSB on final, behind my aircraft. I was expecting a cleared for takeoff call, but it never came…. I believe this incident can be attributed to, my experience at the airport (in contrast to experience at ZZZ1) and feeling pressured to 'get moving' due to the heavy flow of traffic into the airport…*

Errors significantly outnumber violations, with skill-based errors emerging as the most common subtype. This indicates that failures during routine, well-practiced tasks are more prevalent than deliberate rule violations or poor high-level decisions. Smaller contributions are observed at the Preconditions for Unsafe Acts and Supervisory Factors levels, where communication, coordination, and planning issues appear as notable contributors. This finding suggests that active failures at the operator level are the most visible contributors.

Discussion

These findings suggest a need to further understand the student and instructor social dynamics inside the cockpit. Research from educational contexts suggests that the interplay of positional and epistemological framing of uncertainty plays a role in how students solve problems collaboratively [2]. Drawing a clearer parallel for aerospace and aviation educators, cockpit training environments function similarly to collaborative classroom learning settings: both involve shared problem-solving, negotiation of understanding, and coordination under varying levels of uncertainty. In both contexts, how individuals position themselves socially (e.g., authority, confidence, willingness to question) directly affects learning and performance outcomes.

In the aviation training, strengthening positive positional framing and open reporting may improve how student pilots and instructors manage cockpit uncertainty. This aligns with findings from previous studies [6] – [9] which show the influence of social dynamics in high-risk operational settings. From a human-factors perspective, our findings offer insight into underlying issues associated with uncertainty. These findings align with prior research indicating that pilot error accounts for the majority of incidents [17] – [19]. Our study further highlights that many of these errors are skill-based. While skill-based errors are expected in training environments where student pilots are still developing proficiency, the interaction between developing proficiency and uncertainty framing reveals important pedagogical opportunities.

Since simulators are already part of training [21], they provide a practical setting to implement structured uncertainty-based interventions. In this controlled environment, students and instructors can engage in high-risk scenarios involving uncertainty to promote precautionary decision-making and early exposure to challenging conditions. Based on the identified patterns, simulated scenarios can intentionally introduce ambiguous instructions or partial information to prompt clarification and uncertainty reporting. Structured pauses can encourage verbalization of uncertainty and debrief sessions can include guided reflection on how uncertainty was recognized and communicated.

The classroom-cockpit analogy further underscores the importance of psychological safety. Just as collaborative learning research emphasizes the value of safe classroom environments, flight training benefits when student pilots feel comfortable expressing uncertainty. Training design should promote positive positional framing, where student pilots are encouraged to ask questions and seek clarification, and instructors intentionally foster non-hierarchical communication. For example, instructors acknowledging their own mistakes and inviting student input may reduce anxiety and improve knowledge application (e.g., in ACN 2198951, the student pilot knew the rudder correction but over-corrected, possibly due to nervousness). Providing constructive feedback when students encounter uncertainty (e.g., normalizing confusion during learning) may further strengthen learning outcomes.

Beyond simulator training, the proposed framework has implications for university flight programs and aerospace engineering curricula. The framework offers a structured way to teach students how uncertainty emerges and propagates within safety-critical systems, particularly in aerospace systems engineering courses. By incorporating example-based cases, students can better understand human–system integration, hazard analysis, and risk-informed design, linking theoretical systems engineering principles to realistic operational practice.

While additional design recommendations can be derived from specific cases, effective interventions should account for the nature and source of uncertainty in each context to design targeted educational and safety-focused strategies.

Conclusion and Future Work

This study demonstrates that integrating uncertainty framing with the HFACS framework enables a more holistic understanding of aviation incidents in training contexts. By examining how uncertainty is experienced, communicated, and managed between student pilots and instructors, the proposed framework extends traditional human-factors analysis and provides a structured approach to interpreting cockpit dynamics. The findings inform flight training design, Crew Resource Management (CRM) training, and aerospace engineering curricula.

Ultimately, this work seeks to bridge educational theory and aviation safety practice by linking collaborative learning concepts with operational training environments. In doing so, it offers actionable insight into how uncertainty can be incorporated into simulator-based training, instructional flight design, and aerospace systems engineering education to strengthen decision-making and safety outcomes.

This study also highlights linguistic marker of uncertainty within the ASRS reports, laying the foundation for further large-scale analysis. Future research will explore data-mining and artificial intelligence techniques to support automatic coding of uncertainties and expand the dataset beyond the past ten years. Such analysis can also reveal shifts in student-instructor dynamics across time. Such approaches may highlight additional dynamics, including air traffic control coordination. These findings also suggest potential adjustments in balancing ground school, simulator, and in-flight training hours for student pilots. In the long term, this work may extend to human-autonomy teaming applications, including AI-assisted co-pilot systems in manned aircraft and emerging autonomous air mobility contexts.

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