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Optimizing Adaptive Automation in Aviation: A Literature Review on Dynamic Automation System Interaction

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14. ABSTRACT

This literature review examines the evolution of adaptive automation in aviation, comparing foundational research with modern advancements (2013-2023) to identify best practices for future automated systems. Automation has been pivotal in reducing pilot workload and enhancing safety; however, it also introduces challenges such as over-reliance, disengagement, and diminished situational awareness. With the growing complexity of modern military aircraft systems and increasingly dynamic operational environments, adaptive automation offers a promising solution by dynamically adjusting to the pilot's workload and environmental conditions. Key areas explored include automation activation processes—static, adaptable, and adaptive—and their respective impacts on safety and operator performance. Literature review findings emphasize the importance of maintaining situational awareness, particularly during automation handoffs. Transparency in automation interfaces is crucial, ensuring pilots remain informed about system decisions and actions both in real-time and in near-future projections. This is especially important in high-stakes environments, where failure to properly manage automation transitions can lead to catastrophic outcomes.

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The review concludes with recommendations for future adaptive automation systems in aviation, focusing on dynamic task allocation, human-centered interface design, and enhanced transparency to optimize safety and performance. By addressing the risks of automation misuse and disuse, adaptive systems can support human operators while leveraging the strengths of automation to manage increasingly complex aviation scenarios. These guidelines offer a foundation for future research and system development in adaptive automation.

Summary

This literature review examines the evolution of adaptive automation in aviation, comparing foundational research with modern advancements (2013-2023) to identify best practices for future automated systems. Automation has been pivotal in reducing pilot workload and enhancing safety; however, it also introduces challenges such as over-reliance, disengagement, and diminished situational awareness. With the growing complexity of modern military aircraft systems and increasingly dynamic operational environments, adaptive automation offers a promising solution by dynamically adjusting to the pilot’s workload and environmental conditions. Key areas explored include automation activation processes—static, adaptable, and adaptive—and their respective impacts on safety and operator performance. Literature review findings emphasize the importance of maintaining situational awareness, particularly during automation handoffs. Transparency in automation interfaces is crucial, ensuring pilots remain informed about system decisions and actions both in real-time and in near-future projections. This is especially important in high-stakes environments, where failure to properly manage automation transitions can lead to catastrophic outcomes. The review concludes with recommendations for future adaptive automation systems in aviation, focusing on dynamic task allocation, human-centered interface design, and enhanced transparency to optimize safety and performance. By addressing the risks of automation misuse and disuse, adaptive systems can support human operators while leveraging the strengths of automation to manage increasingly complex aviation scenarios. These guidelines offer a foundation for future research and system development in adaptive automation.

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Introduction

Aviation stands at the forefront of automation adoption, driven by the critical nature of its operations. The potentially catastrophic consequences of automation failures or misunderstandings in this field have paradoxically fueled a strong appetite for technological advancement. This urgency has positioned the aviation industry as a pioneer in automation, making significant early investments and setting standards that other sectors often emulate. The industry's proactive approach to integrating and refining automated systems is a model for balancing innovation with the paramount safety concern in high-stakes environments. (e.g., Young et al., 2007). This has been seen in practically all aspects of aviation including fabrication (e.g., Peck, 1959), record keeping (e.g., Zimmerman et al., 1964), air traffic control (e.g., Hink, 1974; Couluris et al., 1978), and most of the systems running in parallel to control aircraft.

Automation retrofits have been of significant interest in both experimental variants and model updates to the UH-60 Black Hawk helicopter. In 2022, aviation history was made as the UH-60 Black Hawk helicopter completed its first fully autonomous flight, marking a significant milestone in unmanned military aircraft technology. Recent technological advancements have expanded the possibilities for automation in various fields (Whalley et al., 2016). While current systems often rely on manually selected automated processes, integrating active sensing technologies—monitoring operator physiology and control behaviors—promises to further accelerate the development and implementation of advanced automation capabilities. If automation can be rapidly enabled when a pilot is compromised in an extreme event, it is likely to save lives and airframes. Additionally, suppose automation is dynamically adjusted in response to the pilot’s sensed state. In that case, it may be possible to reduce or eliminate task overloading and task underloading, both of which have negative impacts on safety and performance, among other negative consequences.

It was well known over half a century ago (see Warren, 1956) that the complexities of operating an aircraft can cause cognitive demand to exceed human capacity. Hence the reduction of task difficulty through automation is a practical necessity. Unfortunately, high degrees of automation in aviation come with their own hazards. If automation results in understimulation, boredom, and monotony, it may become a source of stress and performance decreases (e.g., Thackray, 1980; De Waard, 1996) leading to additional safety hazards. Kayes and Yoon (2022) reviewed how cognitive offloading to automation has led to aviation accidents and systemic issues in aviation training. They additionally detail how a combination of training and manual override of automated systems averted a potential disaster during the Apollo 11 landing. With these issues in mind, it is clear that the concept of automation must be approached carefully and systematically.

This literature review focuses on the conceptual use of future automation systems that are currently the target across many research programs in aviation. The overarching goal is to provide a list of modern automation implementation guidelines tailored explicitly to adaptive automation use in future aircraft. A general overview of past work in the automation space is provided as a solid foundation upon which modern research (i.e., over the last decade) has built upon to reach this technological innovation. Finally, a list of adaptive automation recommendations from the literature is synthesized and discussed.

The Flavors of Automation Activation

Automation, like fire, is a good servant, but a bad master. That is to say, automation is a versatile tool we have at our disposal to assist our needs in highly complex environments, but if it is utilized carelessly, it could result in disaster. Automation can be defined as having technology carry out specific functions that a human operator would typically perform (Parasuraman et al., 2000). The offloading of a task to technology releases the operator from the burden of performing the task, freeing their cognitive resources for use in another task or task-adjacent functions that may involve higher cognitive processing, such as judgement or improvisation. This approach is attractive in highly complex and quickly changing scenarios, such as aviation, where computer reaction time and processing can easily outpace a human many times over. This process begins to highlight the fact that there are things humans are better at and things that machines are better at (the HABA-MABA framework). Automation should leverage these differences to support both the human and machine dynamically (Fitts, 1951).

Here, we define the granularity of focus in automation development for this review. There are many types of automated systems that can be discussed at length, each with technical manuals, training programs, and error codes that would be too much to condense into a meaningful paper. Moving one step further into abstraction enables the discussion of classes of automation (i.e., acquisition, analysis, decision, and action automation systems) and levels of automation (i.e., the balance of human-machine autonomy). For a review of specific classes and levels of automation, see Parasuraman et al. (2000). Here, we focus on the different types of automation system *activation processes*, i.e., how the automation system is initiated.

There are three primary ways in which an automation system can be activated: static automation, adaptable automation, and adaptive automation. Static automation refers to fixed, predefined automation levels where the division of tasks between the human operator and the automated system does not change dynamically based on real-time conditions. In static automation, the control and tasks are allocated at a particular level, and this division remains constant throughout the operation. Human operators may switch different automation modes on or off. However, the system does not adapt to changes in workload, performance, or situational awareness.

Static automation is commonly used in aviation, where systems such as autopilot or flight management systems (FMS) operate at set levels of automation. For example, a pilot may switch on the autopilot to manage the flight path. However, the level of automation remains consistent unless the pilot manually intervenes. Static automation can improve efficiency by reducing pilot workload during routine tasks but may lead to challenges when unexpected or dynamic situations arise, as the system cannot adjust automatically to these changes. Additionally, potential risks of misuse, disuse, and skill degradation are heightened when using static automation systems.

Adaptable automation refers to systems where the human operator can manually adjust the level or type of automation based on preferences or situational demands. The human user controls how the automation behaves and can decide when and how to change the degree of automation to suit different tasks or conditions. In adaptable automation, the system provides flexibility by allowing the human operator to customize automation features. For example, a pilot might choose to increase or decrease the level of automation based on workload, environmental conditions, or specific flight phases. This customization can help pilots balance automation and manual control, reducing cognitive load when necessary while maintaining situational awareness and control. However, the system does not automatically adapt based on real-time inputs, and the responsibility for selecting the appropriate level of automation remains with the human user. This adds an additional task and action sequences that can be intrusive on already overtaxed pilots.

Adaptive automation has gained significant attention in the aviation domain. This system is designed to enhance performance, safety, and efficiency by automatically adapting the level of automation based on the operator's current workload and situational demands. The system dynamically adapts to provide automation as needed, without requiring manual intervention from the human operator. Adaptive automation is a more advanced form of automation implementation that puts the burden on the technology to adjust to the operator's needs in real-time. For instance, if a system detects that a pilot's cognitive workload is too high, it might increase the level of automation to reduce task demands. Conversely, when workload is low, the system may reduce automation to keep the pilot engaged. Adaptive automation is especially valuable in dynamic environments like aviation, where operator performance can fluctuate rapidly based on situational factors. This form of automation relies on physiological monitoring (e.g., electrocardiogram (ECG), electroencephalogram (EEG), and eye tracking) or context specific factors (e.g., mission type, phase of flight, task performance metrics, etc.) to determine when and how to adapt automation levels.

Adaptive automation has become an increasingly essential topic in aviation due to the growing complexity of modern aircraft systems, evolving operational demands (Ward, 2020; Miller, 2023), and the shift toward more autonomous functions (BAE Systems, 2020; Rowan, 2023). The need to optimize adaptive automation in aviation has driven researchers to focus on how automation systems can dynamically adjust to the needs of the human operator, particularly in high-stress, high-stakes environments like flight. While automation is generally seen as a tool to reduce pilot workload and enhance operational efficiency, it brings various challenges, especially regarding automation handoff strategies, automation revocation, and interface design. Implementing these features effectively ensures safety, situational awareness, and operator trust.

Foundational Work in Adaptive Automation

Foundational research on human-automation interaction provides a general understanding of how adaptive automation systems can be optimized for aviation as technology advances. The theoretical framework proposed by Parasuraman et al. (2000) serves as a cornerstone for understanding the different levels of automation and their implications for human operators. The taxonomy of automation, which categorizes automation functions ranging from simple information processing to complete system control, outlines the importance of flexibility in adaptive automation systems. Building off this framework, the Endsley (1995) situation awareness model's recommendations for situational awareness preservation during handoffs to and revocations from automated systems, Sheridan and Verplank's (1996) stress on transparency of automated systems, and Billings' (1997) emphasis on human-centered automation design provide a set of recommendations future adaptive automation systems should incorporate.

Based on this foundational research, several key recommendations for optimizing adaptive automation in aviation emerge:

1. **Dynamic Levels of Automation**: Automation systems should dynamically adjust the level of automation based on real-time assessments of the pilot's cognitive workload and the complexity of the task at hand. This flexibility ensures that the system provides the appropriate level of support without disengaging the pilot from critical decision making (Parasuraman et al., 2000).
2. **Maintaining Situational Awareness**: Adaptive automation systems should be designed to maintain situational awareness during automation handoffs and throughout flight. Interfaces must present relevant information in a clear and timely manner, helping pilots perceive, comprehend, and project the aircraft's state and the surrounding environment (Endsley, 1995; Kaber & Endsley, 2004).
3. **Transparent Decision Making**: Automation systems must be transparent in their decision making processes, providing pilots with clear explanations for their actions. This is particularly important during handoffs or automation revocation, where the pilot needs to understand why the system is taking or relinquishing control (Sheridan & Verplank, 1978; Billings, 1997).
4. **Human-Centered Design**: Automation systems should be designed with a focus on supporting the pilot's cognitive processes, ensuring that the system's actions are predictable, explainable, and easy to understand. Interfaces must present information in a way to minimize cognitive load while keeping the pilot engaged and informed (Wiener, 1989; Billings, 1997).
5. **Automation Handoffs and Revocation**: Handoffs between human and automated control should be seamless, with clear signals for when and why control is being transferred. Similarly, automation revocation should be handled smoothly, with ample warning and clear communication about the system's status and performance (Kaber & Endsley, 2004; Parasuraman et al., 1996).
6. **Preventing Over-Reliance**: Systems should be designed to prevent over-reliance on automation by keeping pilots engaged with the task at hand and ensuring that they remain aware of the system's limitations. Transparent communication about the system's capabilities and limitations can help prevent complacency and ensure that pilots are prepared to intervene when necessary (Parasuraman & Riley, 1997).

These recommendations form the basis for future research and development in adaptive automation, ensuring that aviation systems continue to evolve in ways that support human operators while optimizing performance and safety.

Methods

A literature review was conducted to explore the literature associated with adaptive automation in the aviation domain over the past ten years (2014 to 2023). Literature searches were conducted across four databases: PubMed, Institute for Electrical and Electronics Engineers (IEEE), Web of Science, and Google Scholar (using the Publish or Perish software to facilitate article information downloads; Harzing, 2007). Each search consisted of a combination of independent and dependent variable lists of terms relevant to topics under the conceptual umbrella of adaptive automation. All searches were paired with a Boolean "AND" operator to connect the articles to the key field term "aviation."

The list of independent variables included conceptual terms relating to adaptive automation:

> *"Adaptive Automation," "Human System Integration," ("Automation Handoff" OR "Automation Revoking"), ("Ubiquitous Computing" OR "Pervasive Computing")*

The list of dependent variables included cognitive states and served as potential classification triggers for adaptive automation systems:

> *("Mental Workload" OR "Cognitive Workload"),* "Fatigue," *"Situational Awareness"*

An example of a search conducted for this literature review combines a term from the independent variable list with a term from the dependent variable list and the aviation field term connected by Boolean "AND" operators:

> *"Adaptive Automation" AND ("Mental Workload" OR "Cognitive Workload") AND "Aviation"*

Results from each search were downloaded, tallied, and organized by the databases, independent variables, and dependent variables. To reduce the overall number of articles for full review, a screening process was utilized to remove duplicate articles and screen article titles and then abstracts for relevancy. Duplicates and non-English articles were removed both using automated tools and manual inspection.

The screening processes were conducted using a set of guidelines developed by the reviewers. The guidelines were limited to assessing if the article alludes to a focus on the application of adaptive automation (i.e., using a list of keywords to help identify relevant articles), identifying if external factors were highly manipulated to the point where the study may be irrelevant to general adaptive automation use (i.e., studies looking at drug effects or abnormal populations), and determining if another field was analyzed besides aviation (e.g., many articles mention the aviation field in their background sections but the study may not be focused on aviation). This process was first conducted on the titles and then the abstracts to narrow the focus of this literature review.

The final article list was then narrowed further to provide a final list of relevant articles for thorough reading and dissection. Due to the many automation systems tested in the reviewed articles being of varying types, technological readiness, and application levels, an analysis of the final article list focused on identifying what automation recommendations were put forth by modern research in the aviation domain. These recommendations were then evaluated across articles to provide a modern consensus on the key considerations that should be incorporated into automation systems. This literature review reports the key findings relevant to adaptive automation recommendations for future systems.

Results

A total of 2555 articles were extracted from the four databases. Figure 1 depicts search process results and details how many articles were removed from the total during each step of the review. Most articles were retrieved from the IEEE database, with 2403 articles pulled from it alone. Roughly half (1229) of the articles retrieved across all four databases were duplicates, indicating IEEE results had high levels of overlap across the different search term combinations. Title screening removed another majority of the articles (939), while abstract screening (254) narrowed the final article review list to 133 articles. The full-text articles were retrieved for all 133 articles in the final review.

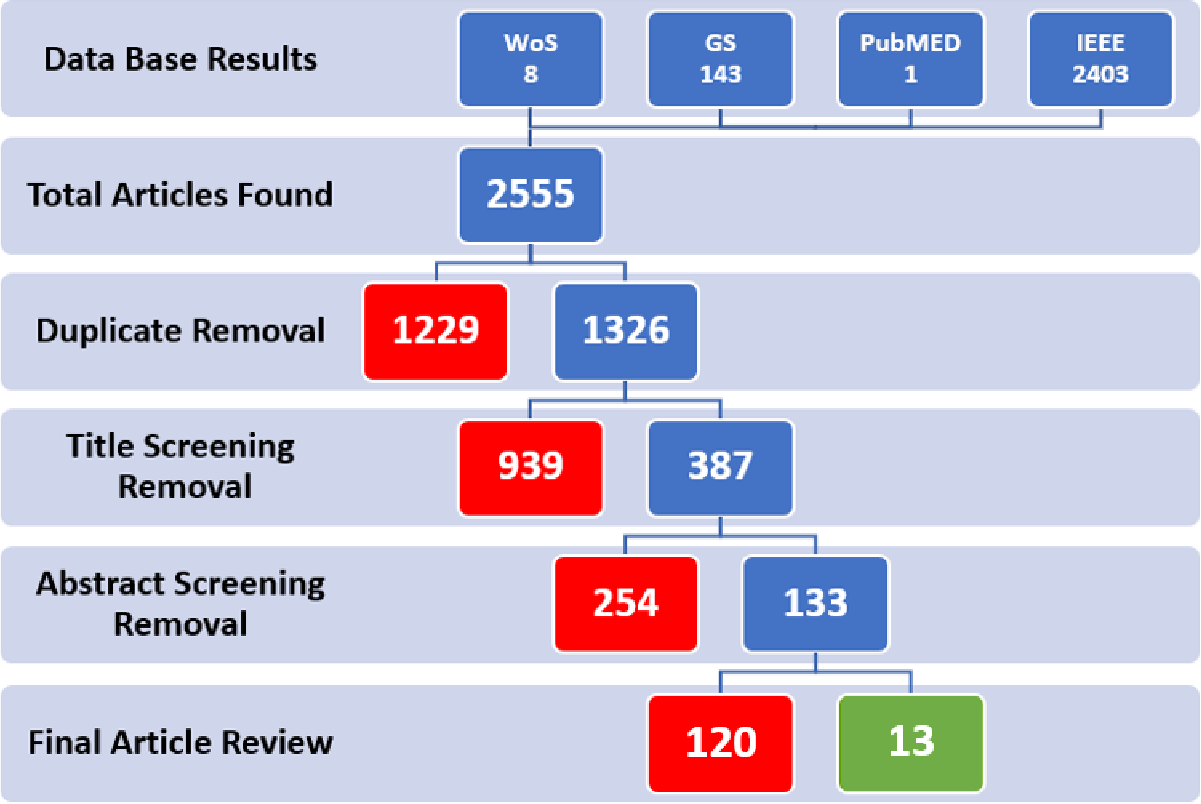

Figure 1. Visualization of the literature review process. Red boxes indicate the number of articles removed from the pool. The green box represents final article total.

During the final article review, it became clear that most of the remaining 133 articles were either literature reviews or design specification and philosophical papers that mentioned the potential use of an operator state monitoring (OSM) system to drive adaptive automation. These articles did not demonstrate any use case of adaptive automation. Furthermore, they did not offer the desired information for the future development of an actual adaptive automation system. As such, the decision was made to remove the literature review and design specification articles during the final article review phase. This led to a total of 13 articles that utilize an adaptive automation application in the aviation domain. The following results are derived from the final 13 articles.

Article Reviews and Adaptive Automation Recommendations

The use of adaptive automation in the reviewed articles spans a variety of specific implementations that are difficult to directly compare in terms of efficiency and feasibility in the general aviation context. However, key findings and recommendations for adaptive automation are abundant in the reviewed literature. This data is far more generalizable and can serve as a solid foundation to assist future work at the United States Army Aeromedical Research Laboratory (USAARL) to design and develop adaptive automation systems for experimental evaluation. Short summaries of the 13 analyzed articles, including adaptive automation recommendations and links to foundational work, are provided in Appendix A.

Using these reviews, ten general adaptive automation recommendations were synthesized by author judgement using the total list of 40 recommendations in Appendix A.

1. ***Enhance automation to dynamically adjust task allocation based on real-time cognitive state monitoring (cognitive workload, fatigue, situational awareness).***
    - *Recommendations: 4, 5, 10, 12, 26, 27, 35, 39*
2. ***Provide real-time feedback and guidance during high-demand or emergency situations, prioritizing situational awareness.***
    - *Recommendations: 1, 3, 6, 11, 28, 32*
3. ***Ensure manual intervention remains an option for pilots, balancing automation and human control to preserve situational awareness and engagement.***
    - *Recommendations: 2, 7, 8, 13, 24, 25, 34*
4. ***Develop adaptive automation systems with customizable and context-sensitive interventions, allowing operators to tailor automation based on individual preferences and cognitive state.***
    - *Recommendations: 13, 14, 15, 18, 37, 38*
5. ***Refine automation interface designs to reduce cognitive workload through simplicity, minimal interaction, and prioritized critical information.***
    - *Recommendations: 13, 14, 17, 31, 33, 40*

6. ***Ensure automation systems enhance pilot decision making without increasing complexity, integrating predictive capabilities and clear, actionable indicators for future behaviors.***
    - *Recommendations: 13, 16, 29, 30, 32*
7. ***Use machine learning and predictive algorithms cautiously, ensuring safety and reliability through rigorous certification and minimal computational complexity.***
    - *Recommendations: 9, 19, 20, 21, 22*
8. ***Incorporate teamwork monitoring and support tools to improve crew coordination and performance in complex environments.***
    - *Recommendations: 15, 36*
9. ***Utilize multisensory feedback (visual, audio, tactile) to improve situational awareness, especially during low-visibility or high-stress scenarios.***
    - *Recommendations: 6, 10*
10. ***Training protocols should focus on enhancing automation understanding, failure detection skills, and manual control reintroduction to maintain situational awareness.***
    - *Recommendations: 8, 15, 23, 24, 34, 37*

These 10 recommendations provide a framework with modern scientific backing and adaptive automation applications readily referenceable. The resulting list will be used as design guidelines for future adaptive automation development at USAARL.

Discussion

The goal of adaptive automation use in aviation revolves around the critical need to design systems that enhance pilot performance, reduce workload, and maintain safety. Each general recommendation serves as an overarching guideline that addresses a specific aspect of adaptive automation. In contrast, the specific recommendations provide actionable strategies to ensure successful implementation. This section expands on the general recommendations, integrating scientific insights from foundational articles to emphasize their relevance and impact.

General Recommendation 1: Dynamic Task Allocation Based on Cognitive State Monitoring

The first general recommendation emphasizes the importance of dynamically adjusting task allocation based on real-time monitoring of cognitive workload, fatigue, and situational awareness. This is essential in aviation, where pilot performance fluctuates under varying stress levels and complexity. Parasuraman and colleagues (2000) introduced a model that outlines the importance of automation that dynamically adapts based on the operator’s state. This aligns closely with specific recommendations, such as integrating EEG-based workload indices to adjust task allocation (Recommendation 4) and offering varying levels of automation depending on real-time workload (Recommendation 5).

One specific strategy is incorporating real-time mental state monitoring to redistribute workload based on cognitive overload or fatigue (Recommendation 35). For instance, automation systems that track and adjust based on the pilot's mental workload can prevent scenarios where pilots are either overwhelmed or under-stimulated. Parasuraman and Byrne (2003) emphasize that adaptive automation in aviation must monitor cognitive workload, fatigue, and attentional lapses to ensure appropriate task allocation and intervention during high-demand scenarios. By adopting systems that can dynamically adjust task difficulty and intervention strategies based on cognitive workload, aviation systems can improve pilot performance while reducing the risks associated with high cognitive workload or fatigue. This aligns with foundational research by Hancock and Scallen (1996), underscoring the importance of adaptive function allocation optimizing operator performance.

General Recommendation 2: Real-Time Feedback and Guidance During High-Demand or Emergency Situations

Real-time feedback on automation state and decision making processes ensures that pilots receive the most critical information at the right time, reducing their cognitive load and helping them stay focused on the most important tasks. Providing real-time automation feedback during high demand tasks or emergencies is critical for maintaining situational awareness and ensuring that pilots can make informed decisions under pressure. Endsley (1995) emphasized that situational awareness is a dynamic process that requires continuous updates and feedback, especially in fast-changing environments like aviation. Specific recommendations that support this principle include using enhanced situational awareness tools that incorporate visual and auditory cues to help pilots focus in high-demand scenarios (Recommendation 6).

Additionally, providing real-time cognitive monitoring and adaptive feedback during emergencies (Recommendation 28) can be particularly useful for guiding pilots through off-nominal events, such as system failures or unexpected flight conditions. By integrating real-time cognitive monitoring and feedback systems into aviation operations, adaptive automation systems can enhance situational awareness, reduce the likelihood of errors, and improve decision making during high-stress situations. This aligns with foundational research by Sarter and Woods (1997), who explored the role of real-time feedback in preventing automation surprises and maintaining operator situational awareness.

General Recommendation 3: Ensuring Manual Intervention and Balancing Automation with Human Control

The third general recommendation underscores the importance of ensuring that manual intervention remains an option, balancing automation with human control. This recommendation is closely tied to Parasuraman and Riley's (1997) discussion on the risks of over-reliance on automation, where pilots may become disengaged or unprepared to take control in the event of system failure. Ensuring that pilots remain engaged and can intervene when necessary is critical to maintaining safety and situational awareness. Specific recommendations such as allowing pilots to override automation in case of failure (Recommendation 7) and periodically reintroducing manual control to prevent disengagement (Recommendation 24) support this guideline. These strategies ensure that pilots stay proficient in manual operations and remain actively engaged in monitoring the system. This is particularly important during extended periods of high automation, where the risk of complacency is greater.

By periodically requiring pilots to take control of the aircraft and practice manual intervention, adaptive automation systems help prevent over-reliance on automation, ensuring that pilots are prepared to take action if needed. Billings (1997) emphasized that human-centered automation should prioritize the pilot's ability to intervene and maintain control, even in highly automated environments.

General Recommendation 4: Customizable and Context-Sensitive Interventions

Adaptive automation systems should allow for customizable and context-sensitive interventions, enabling pilots to tailor the system based on individual preferences and cognitive state. Inagaki (2003) discussed the importance of context-sensitive adaptive strategies in human-automation interaction, where the system adjusts based on task demands and the operator's abilities and preferences. Specific recommendations such as offering customizable automation options (Recommendation 18) and selectively implementing interventions based on cognitive state (Recommendation 38) highlight the importance of flexibility in adaptive automation. For instance, pilots should be able to adjust the level of automation depending on their workload, experience, and the flight phase. Additionally, adaptive automation systems driven by physiological input must be tailored to the individual pilot to perform optimally. This flexibility allows for a more personalized interaction with automation, reducing the risk of cognitive overload while maintaining situational awareness in a way that is tailored to the individual (rather than using a generic one-size-fits-all solution). Tailoring automation to the needs and preferences of individual pilots also improves trust in the system. Providing transparency in how the system adjusts to the cognitive state or flight phase, such as offering real-time explanations of decision making processes (Recommendation 14), can enhance pilot confidence in automation.

General Recommendation 5: Refining Automation Interface Designs to Reduce Cognitive Workload

The design of automation interfaces plays a significant role in reducing cognitive workload and improving pilot performance. Wickens and Hollands (1999) highlight that well-designed interfaces present clear and actionable information and are critical to reducing cognitive load. The fifth general recommendation emphasizes simplicity, minimal interaction, and prioritized information to help pilots focus on critical tasks without becoming overwhelmed.

Specific recommendations include integrating clear, actionable visual indicators (Recommendation 31) and designing interfaces that reduce clutter and simplify interactions (Recommendation 33). For example, systems that consolidate critical information into a single interface (Recommendation 17) can reduce the need for pilots to navigate through multiple menus or screens during high-stress scenarios. Additionally, interfaces prioritizing route preview tools and real-time alerts (Recommendation 14) ensure that pilots receive timely, relevant information without being overloaded by unnecessary details. By refining automation interface designs to focus on simplicity and clarity, adaptive systems can reduce cognitive workload, allowing pilots to maintain situational awareness while interacting with the automation. This aligns with foundational research by Parasuraman et al. (2000), which emphasizes the importance of designing automation systems that complement, rather than complicate, pilot decision making.

General Recommendation 6: Enhancing Pilot Decision Making Without Increasing Complexity

Automation systems should enhance pilot decision making by providing clear, actionable information without increasing complexity. This principle is essential to preventing cognitive overload, particularly in high-stress or complex flight phases. Parasuraman et al. (2000) argue that automation should assist decision making without overwhelming the operator with excessive or complex information.

Specific recommendations such as integrating predictive capabilities that show real-time insights into future system behaviors (Recommendation 29) and extending trajectory predictions beyond short intervals (Recommendation 30) are crucial to achieving this balance. Predictive automation displays, such as advanced decision windows (ADW), can give pilots a clear understanding of what the system is doing and what it will do next, reducing uncertainty and enhancing situational awareness without adding complexity. By integrating these predictive capabilities, adaptive automation systems can support pilots in making informed decisions without overburdening them with data. This approach is supported by foundational research by Endsley (1995), which highlights the importance of clear, actionable information in maintaining situational awareness during dynamic tasks.

General Recommendation 7: Cautious Use of Machine Learning and Predictive Algorithms

While machine learning and predictive algorithms hold promise for adaptive automation, their use must be approached cautiously to ensure safety and reliability. Parasuraman and Riley (1997) warned against using automation, particularly in safety-critical environments where unpredictable system behavior could have serious consequences. Specific recommendations such as ensuring rigorous certification of machine learning algorithms (Recommendation 9) and using minimal features to reduce computational complexity (Recommendation 21) underscore the need for caution. Machine learning algorithms, while capable of enhancing predictive accuracy, should not introduce unnecessary complexity or uncertainty into the system. Unsupervised learning techniques that continuously monitor spatial disorientation (SD) without requiring labeled data (Recommendation 22) are one example of how machine learning can be applied safely and effectively. Adaptive automation systems can enhance performance without compromising safety by integrating machine learning cautiously and ensuring algorithms undergo rigorous testing and certification.

General Recommendation 8: Incorporating Teamwork Monitoring and Support Tools

Teamwork is crucial to aviation, and adaptive automation systems must support effective crew coordination. Kaber and Endsley (2004) emphasized the importance of shared situational awareness among crew members, particularly in complex environments where teamwork is essential to mission success. Specific recommendations such as incorporating teamwork monitoring tools (Recommendation 15) and integrating support systems to facilitate better communication (Recommendation 36) are essential for improving crew coordination. Adaptive automation systems can ensure that crew members work together efficiently and effectively, even in high-stress situations, by providing real-time feedback on team performance and supporting effective communication. By improving teamwork and collaboration, adaptive automation systems can enhance overall crew performance and reduce the likelihood of errors caused by miscommunication or uneven situational awareness.

General Recommendation 9: Utilizing Multisensory Feedback to Improve Situational Awareness

Multisensory feedback, which includes visual, auditory, and tactile cues, can significantly improve situational awareness, particularly in low-visibility or high-stress environments. Wickens (2002) noted that different sensory modalities can support situational awareness by providing redundant information through multiple channels, reducing the risk of missing critical cues. Specific recommendations such as integrating multisensory feedback systems (Recommendation 6) and incorporating modality-specific alarms relative to the predicted cognitive state (Recommendation 10) support this approach. By providing information through multiple sensory channels, adaptive automation systems can ensure that pilots receive critical cues even when visual or auditory channels are compromised. By leveraging multisensory feedback, adaptive automation systems can improve situational awareness and prevent spatial disorientation, especially during challenging flight conditions.

General Recommendation 10: Training Protocols to Enhance Automation Understanding and Maintain Situational Awareness

Training is critical in ensuring that pilots can effectively interact with automation, understand its behavior, and intervene when necessary. Billings (1997) emphasized that human-centered automation requires comprehensive training programs that enhance the operator's understanding of how automation functions and how to detect failures. Specific recommendations such as developing training protocols that expose pilots to system failures (Recommendation 23) and periodically reintroducing manual control to maintain engagement (Recommendation 24) are essential for ensuring that pilots remain proficient in manual operations. Additionally, training programs should focus on enhancing pilots' ability to detect and recover from failures (Recommendation 34) and optimizing the system based on individual experience levels (Recommendation 15). By implementing comprehensive training protocols, adaptive automation systems can ensure that pilots remain engaged, maintain situational awareness, and are prepared to take manual control when needed.

Summary

The general recommendations for adaptive automation in aviation provide a comprehensive framework for enhancing pilot performance, reducing cognitive workload, and improving safety. Each recommendation is supported by specific strategies that offer actionable approaches for implementing adaptive automation in a way that complements, rather than complicates, pilot tasks. Foundational research in human-automation interaction supports these principles, emphasizing the importance of dynamic task allocation, real-time feedback, teamwork, multisensory feedback, and comprehensive training in creating effective adaptive automation systems. Following these guidelines, the aviation industry can develop systems that enhance human performance, reduce errors, and improve overall flight safety.

Conclusion

The future of adaptive automation in aviation is poised to transform the landscape of human-machine collaboration, promising advancements in safety, efficiency, and pilot performance. Based on the comprehensive review of current research, several key themes emerge that highlight both the potential and the challenges of adaptive automation systems in aviation. These systems must balance reducing cognitive workload with maintaining operator situational awareness, trust, and engagement. Real-time cognitive assessments, dynamic task allocation, and multisensory feedback represent promising solutions to optimizing human-automation interaction, ensuring that pilots receive support during high-demand situations while staying involved and alert.

Central to the success of future adaptive automation systems is the integration of transparent and intuitive interface designs. Systems that clearly communicate their actions and logic to the operator will foster greater trust, reducing the need for frequent verification and manual intervention. Transparent automation, combined with ergonomic interfaces, such as adaptive head-up displays and touch screens, will enhance pilot performance by minimizing cognitive strain and improving situational awareness. Moreover, the use of multisensory feedback, including tactile and auditory cues, will further support pilots in complex environments where visual information may be compromised, ensuring they maintain spatial orientation and control.

One of the key findings from the review is the importance of flexible automation handoffs and revocation mechanisms. As automation takes on more critical roles in managing routine and emergency tasks, ensuring seamless transitions between automated and manual control is essential to maintaining operator engagement and preventing "out-of-the-loop" unfamiliarity. Systems that allow for varying levels of automation, and real-time workload monitoring tools, such as EEG-based adaptive automation systems, provide valuable models for future developments. Training protocols that expose pilots to frequent system failures and transitions can help build the skills necessary to effectively manage these handoffs.

Ultimately, the future of adaptive automation in aviation will depend on the industry's ability to address human factors concerns while integrating advanced technologies like machine learning, real-time physiological monitoring, and predictive feedback systems. The next generation of adaptive automation must enhance operational efficiency and ensure that pilots remain active, informed decision makers. Adaptive automation systems will lead to safer, more reliable, and more efficient aviation operations through careful attention to transparency, interface design, workload management, and automation flexibility. This ongoing evolution in technology will support the growing complexity of flight operations, helping to meet the demands of modern aviation while reducing the cognitive burden on human operators.

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Appendix A. Reviewed Article Synopses

1. A Holographic Checklist Assistant for the Single Pilot (Pérez & Behrend, 2022)

This study explored the use of an augmented reality (AR)-based system called Pilot Assist, integrated with Microsoft HoloLens, to enhance single pilot operations (SPO). The system uses holographic checklists and real-time guidance to reduce pilot workload and provide visual and auditory support during critical phases of flight. However, concerns were raised about hardware limitations and discomfort, especially in non-routine scenarios.

- **Recommendations:**

    1. AR systems should be further refined to reduce cognitive workload by automating routine procedures and providing enhanced support during high-stress situations.
    2. Automation systems should complement, not replace, human redundancy by incorporating ground support or remote monitoring.
    3. Future iterations should enhance handling of off-nominal scenarios by providing real-time feedback and guidance during emergency situations.

Evolution from Foundational Work: The use of AR to reduce cognitive workload aligns with Parasuraman et al. (2000), who advocated for dynamic automation levels. This system demonstrates an evolution from early automation handoffs by providing continuous, transparent guidance, although transparency in off-nominal situations remains a challenge.

2. Adaptive Automation Triggered by EEG-Based Mental Workload Index (Aricò et al., 2016)

This study introduced a passive brain-computer interface (pBCI) that triggers adaptive automation based on real-time EEG measurements of mental workload. The system was tested in air traffic control (ATC) environments and successfully activated automation during periods of high demand, improving performance and reducing workload.

- **Recommendations:**

    4. EEG-based workload indices should be integrated into adaptive automation systems to monitor mental workload and dynamically adjust task allocation.
    5. Systems should offer varying levels of automation based on real-time workload, ensuring that pilots are neither overloaded nor underloaded.
    6. Enhanced situational awareness tools, including visual and auditory cues, should be used to improve focus during high-demand scenarios.

Evolution from Foundational Work: This study builds on Endsley (1995) and Parasuraman et al. (2000) by introducing real-time physiological monitoring to trigger adaptive automation. The use of EEG data for dynamic adjustment represents a significant advancement in how automation systems manage workload and handoffs.

3. Flight Procedures Automation: Towards Flight Autonomy in Manned Aircraft (Alvarez et al., 2020)

The Cockpit Automation Procedures System (CAPS) automates cockpit procedures in manned aircraft, offering four levels of automation, ranging from manual control to full autonomy. The system is designed to reduce pilot workload during abnormal and emergency situations and is part of a broader initiative toward autonomous flight.

- **Recommendations:**

7. Automation systems must allow for manual intervention in case of system failure, and pilots should always retain the ability to override the automation.
8. Automation systems must maintain a balance between reducing workload and preserving pilot situational awareness. Enhanced training modules or displays should be used to keep pilots engaged.
9. Machine learning algorithms, while promising, must undergo rigorous certification to ensure safety and reliability in dynamic environments.

Evolution from Foundational Work: CAPS advances Billings' (1997) concept of human-centered automation by offering varying levels of autonomy based on the situation. It emphasizes the importance of automation revocation, particularly during emergencies, which aligns with Endsley's (1995) warnings about the impact of sudden control transfers on situational awareness.

4. A pBCI to Predict Attentional Error Before it Happens in Real Flight Conditions (Dehais et al., 2019)

This study developed a pBCI designed to predict inattentional deafness in pilots by analyzing EEG data. The system anticipates when pilots are likely to miss auditory alarms due to cognitive overload and adjusts the delivery of critical information.

- **Recommendations:**

10. Adaptive automation systems should predict attentional lapses and adjust alarm modalities based on the operator's cognitive state.
11. Automation should take over routine tasks during periods of predicted inattentional deafness, allowing pilots to focus on higher-priority tasks.
12. Advanced EEG metrics should be integrated to refine predictions and improve system accuracy.

Evolution from Foundational Work: This system enhances Endsley's (1995) model of situational awareness by introducing neuroadaptive automation that can predict cognitive lapses in real-time. The use of EEG data to dynamically adjust alarm delivery is a novel advancement that builds on early transparency recommendations by Sheridan and Verplank (1978).

5. Usability Evaluation of Fleet Management Interface for High-Density Vertiplex Environments (Hodell et al., 2022)

This study evaluated NASA's Fleet Management Interface (FMI) for managing urban air mobility operations. The FMI was designed to assist ground control station operators in managing autonomous flights, and the study focused on improving interface usability, workload management, and trust in automation.

- **Recommendations:**

13. Interface designs should prioritize route preview tools that allow users to visually assess and select appropriate rerouting options.
14. Real-time alerts and notifications should be more detailed, providing contextual information that helps operators make quicker decisions.
15. Systems should be designed to accommodate both novice and expert users, expanding the usability of adaptive automation across various expertise levels.

Evolution from Foundational Work: This study advances the transparency recommendations of Parasuraman and Riley (1997) by emphasizing the importance of clear, real-time information in automation systems. The focus on user-centered design builds on Billings (1997), who argued for interfaces that reduce cognitive load.

6. Effects of Transparency on Pilot Trust and Agreement in the Autonomous Constrained Flight Planner (Sadler et al., 2016)

This study investigated the effects of transparency on pilot trust and decision making when using NASA's Autonomous Constrained Flight Planner. The findings highlight that increased transparency improves trust and reduces the need for pilots to verify the system's recommendations, especially in high-risk scenarios.

- **Recommendations:**

16. Future automation systems should provide detailed explanations of their decision making processes, improving trust and reducing the need for verification.
17. Systems should integrate critical information into a single interface, reducing the need to navigate multiple menus.
18. Customizable automation options should be developed to allow pilots to tailor system recommendations based on personal preferences or specific situations.

Evolution from Foundational Work: This study reinforces the foundational work of Parasuraman and Riley (1997) by confirming the importance of transparency in maintaining trust in automation. The findings also align with Sheridan and Verplank (1978) by demonstrating that pilots are more likely to accept automated recommendations when they understand the system's logic.

7. Simulation and Classification of Spatial Disorientation in a Flight Use Case Using Vestibular Stimulation (Foucher et al., 2022)

This study simulated SD in flight using vestibular stimulation and machine learning models to predict SD occurrence. The findings emphasize the importance of real-time data in predicting and mitigating SD through automation systems, which rely on time-based features from joystick data.

- **Recommendations:**

    19. Future automation systems should leverage long-short term memory architectures for state prediction, as they offer high accuracy with minimal features and data.
    20. Automation systems should integrate multisensory data, such as time, frequency, and positional data, for enhanced prediction accuracy.
    21. SD prediction systems should use minimal features to reduce computational load while maintaining accuracy.
    22. Unsupervised learning techniques should be incorporated to continuously monitor SD during flights without requiring labeled data.

Evolution from Foundational Work: Building on Endsley (1995) and Parasuraman et al. (2000), this study expands the use of real-time data for situational awareness. The focus on real-time vestibular cues and machine learning enhances automation’s predictive capabilities, offering advanced methods for managing disorientation and preserving control in critical situations.

8. Level of Automation and Failure Frequency Effects on Simulated Lunar Lander Performance (Marquez & Ramirez, 2014)

This study examined how different levels of automation and failure frequency impact failure detection during a lunar landing simulation. The results indicate that higher failure frequencies improve detection accuracy, regardless of the level of automation.

- **Recommendations:**

    23. Training regimes should expose pilots to frequent system failures to improve automation failure detection skills.
    24. Manual control should be periodically reintroduced during automated operations to maintain situational awareness and engagement.
    25. Automation systems should balance cognitive offloading with the need for operators to remain engaged and alert to potential system failures.

Evolution from Foundational Work: This study supports Endsley’s (1995) emphasis on the importance of situational awareness, particularly during failure conditions. The findings echo Billings (1997) by reinforcing the need for periodic manual control to prevent over-reliance on automation. This marks a continuation of the conversation on out-of-the-loop unfamiliarity in automation.

9. Validating a "Real-Time Assessment of Multidimensional User State" (RASMUS) for Adaptive Human-Computer Interaction (Schwarz & Fuchs, 2018)

This study validated the RASMUS framework for assessing user cognitive states such as high workload, fatigue, and incorrect attentional focus in real-time. The system identifies performance decrements and adapts accordingly to support the user.

- **Recommendations:**

26. Future systems should incorporate multidimensional user state assessments, focusing not just on workload but on fatigue and attention as well.
27. Adaptive strategies should be context-sensitive, dynamically selecting interventions based on the cognitive state diagnosed.
28. Situational awareness metrics, such as real-time feedback, should be integrated to enhance decision making and reduce attention-related failures.

Evolution from Foundational Work: Building on Parasuraman et al. (2000) and Endsley (1995), this study emphasizes multidimensional cognitive monitoring, introducing an advanced way of detecting operator fatigue and attention lapses in real time. The real-time aspect adds depth to the foundational theories of situational awareness and workload management.

10. Increasing Pilot's Understanding of Future Automation State – An Evaluation of an Automation State and Trajectory Prediction System (Etherington et al., 2019)

This paper evaluated a Trajectory Prediction System that provides real-time predictions of the aircraft's future trajectory and automation states, improving pilot awareness of energy management and reducing surprise during flight.

- **Recommendations:**

29. Automation systems should provide predictive capabilities, showing pilots real-time insights into future automation behaviors.
30. Systems should extend trajectory predictions beyond short intervals, covering entire descent paths or critical flight phases.
31. Clear, actionable visual indicators should be prioritized over textual clutter to enhance pilot awareness.

Evolution from Foundational Work: This study builds on Parasuraman et al. (2000) by extending the concept of automation transparency through predictive displays. It also supports Endsley's (1995) emphasis on maintaining situational awareness by ensuring that automation systems clearly communicate future states to the pilot.

11. Evaluation of Onboard System State and Path Awareness Technologies During Transport Operations (Etherington et al., 2020)

This study evaluated the “Automation Does What?” (ADW) and “Automation Function Configuration” tools, designed to improve pilot awareness of the automation’s current and future state. Both tools enhance understanding of automation transitions, reducing confusion and surprise.

- **Recommendations:**

32. Predictive automation displays like ADW should be integrated into cockpits to provide real-time insights into what the system is doing and what it will do next.
33. Interface designs should prioritize clarity, reducing clutter and focusing on essential information during complex operations.
34. Pilot training should focus on improving understanding of automation behavior, particularly in high-stress or complex conditions.

Evolution from Foundational Work: This study directly follows the recommendations of Parasuraman and Riley (1997) on automation transparency and trust. By offering real-time insights into system behavior, these tools advance the foundational understanding of how clear feedback from automation systems improves trust and reduces the risk of mode confusion.

12. Cooperation and Mental States Neurophysiological Assessment for Pilots' Training and Expertise Evaluation (Borghini et al., 2023)

This paper explores how real-time neurophysiological assessments (such as EEG) can be used to assess pilot cooperation, stress, and workload during training. The system monitors pilots’ mental states and provides adaptive feedback to improve cooperation and performance.

- **Recommendations:**

35. Automation systems should integrate real-time mental state monitoring to adjust task difficulty or redistribute workload based on stress or cognitive overload.
36. Teamwork monitoring should be incorporated into future systems to facilitate better crew coordination.
37. Adaptive systems should provide tailored training sessions based on real-time cognitive feedback to enhance learning efficiency and reduce cognitive strain.

Evolution from Foundational Work: This study expands on Billings (1997) by introducing real-time neurophysiological monitoring to assess team dynamics and individual cognitive states. It also builds on Parasuraman et al. (2000) by providing dynamic adjustments based on real-time mental state assessments.

13. Task-Oriented Adaptive Heads-Up Display (HUD) Human Reliability Analysis (Sichen et al., 2022)

This study compares adaptive HUD systems to traditional HUD systems, focusing on reducing pilot cognitive load during various flight stages. Results indicate that adaptive HUD systems significantly reduce workload and improve task performance, particularly during takeoff and landing.

- **Recommendations:**

38. Adaptive automation systems should focus on dynamically adjusting information presentation based on task difficulty and flight phase.
39. Cognitive load management through real-time monitoring should be integrated into future HUD designs.
40. Interface designs should align with human cognitive patterns, facilitating quicker adaptation and reducing workload.

Evolution from Foundational Work: This study builds on Parasuraman et al. (2000) by introducing task-oriented adaptation in real-time HUD systems. It also aligns with Wiener (1989) by emphasizing the importance of intuitive interface design that complements human cognitive habits.

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