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Assessing The Current State of Augmented Reality Technology in Aviation

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Abstract

The aviation industry is now embracing Augmented Reality (AR) technology and applying it in a variety of ways including maintenance support, pilot training, navigation assistance and operational efficiency. As AR provides the ability to overlay digital data onto the "real world", this technology enhances the user's situational awareness, decreases the probability of human error, and increases the productivity of operations. The purpose of this paper is to determine the status of AR technology in aviation by identifying AR technology's primary applications, the level of readiness to implement the technology, the challenges with AR implementation, and the forecast for future use of AR in aviation. There have been many success stories of AR technology as used in aircraft maintenance and training simulations; however, the practical use of AR in the cockpit has not yet occurred due to certification requirements, safety issues, and technical limitations. This paper provides an overview of current developments with AR technology and suggests research areas that need to be investigated to allow for broader use of AR technology in aviation.Over the last few years, aerospace manufacturers such as Boeing and Airbus have implemented pilot programs for the use of AR-based maintenance assistance and digital workflows to reduce aircraft downtime and improve inspection accuracy. Regulatory agencies such as the FAA and the EASA are investigating the certification procedures for AR-based wearable systems in safety-critical environments. Although there have been numerous successful demonstrations of AR technology, the ability to move from experimental systems to certified operational systems is impeded by the need for human factors validation, system reliability, cybersecurity issues, and the integration of previously existing avionics systems.

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I.NTRODUCTION

Aviation has been continually making use of new technologies to improve its safety, efficiency and overall effectiveness in operations. Augmented Reality (AR) is a relatively new technology that allows for integration of digital visual information with the real world. This can be contrasted with Virtual Reality (VR), where users are fully immersed in a digitally simulated environment, whereas with AR, the perception of the real world is enhanced by overlaying contextual data, instructions or visual cues. There have been numerous technological advancements in the development of AR for use in aviation through the availability of advanced sensors and computer vision, wearable displays, and high performance embedded computing devices. These newer technologies have allowed for the practical utilization of AR in aviation applications such as aircraft maintenance, flight training and navigation systems. Furthermore, advances in the development of tracking algorithms and spatial mapping techniques have enabled digital overlays to remain accurately registered on aircraft components or cockpit instruments in all but the most adverse lighting conditions. Thus, AR systems can provide users with real-time guidance, visually highlight important components and provide context alerts, while allowing the user to maintain their focus on operational tasks.The incorporation of AR technology into aviation is part of a larger effort by aerospace manufacturers (i.e., Boeing and Airbus) to implement digital transformation initiatives that utilize digital twins, predictive maintenance analytics and smart manufacturing technologies. While AR technology facilitates the visualization of digital information associated with the aircraft in real time, it also provides an intuitive representation of complex technical information to the user. In

maintenance environments, technicians can visualize wiring paths or hydraulic systems directly on the aircraft surface. In training scenarios, pilots can interact with physical cockpit controls augmented by digital cues that simulate navigation routes, system failures, or emergency conditions. In spite of these advancements, the practical use of augmented reality (AR) technology under operational flight conditions is limited. The aviation industry is a safety-critical and heavily regulated environment, so all new cockpit technology must be rigorously validated. Governmental authorities, including the Federal Aviation Administration (FAA) and the European Union Aviation Safety Agency (EASA), require extensive testing to ensure that new systems do not add risk. In addition, display latency, registration accuracy, electromagnetic compatibility, redundancy of systems, and cybersecurity all must be fully evaluated before certification. Also, human factors- including cognitive workloads; distribution of attention; and visual distractions- affect how AR will either help or hinder situational awareness in flight operations.

II. OVERVIEW OF AUGMENTED REALITY TECHNOLOGY

Augmented Reality (AR) is the enhancement of physical environments using computer-generated data. The hardware to implement AR in aviation applications includes head-mounted displays (HMDs), tablets, smart glasses, and other devices. The requirements for AR systems in aviation applications require very high precision, low latency, and excellent performance in all types of aviation environments. Depending on the nature of the AR applications, aviation systems can require a level of reliability equal to that of certified avionics systems.

The foundation of AR technology is what is known as spatial registration. Spatial registration is the method used to maintain the virtual objects' alignment with the real-world structures at all times as the user moves. The technology required for achieving spatial registration consists of a combination of inertial measurement units (IMUs),

optical cameras, depth sensors, and in some cases, Global Positioning Systems (GPS) data. Current AR systems use Simultaneous Localization and Mapping (SLAM) algorithms to create a digital representation of the environment using a real 3D perspective. By continually updating the user's location and orientation in real-time, the SLAM algorithms assist in maintaining the accuracy and stability of the virtual objects over the actual aircraft or the cockpit instrumentation, thereby providing augmented-reality capabilities to the user.

Display technologies are crucial to creating effective Mixed-Reality AR experiences. Optical See-Through displays rely on projecting images in real-time over an object with transparent lenses, allowing users to see both the real world and the projected digital content simultaneously. To ensure that displayed information in aviation remains viewable in bright ambient light conditions within the cockpit, displays must have high levels of brightness. Field of view (FOV) limits must also be considered, as well as maintaining proper alignment between the focal depth of the display and viewing distance from the user to provide comfortable (no eye strain) viewing of the information displayed, while also being able to provide the viewer with a true perception of depth.New developments in waveguide optics and micro-OLEDs have provided increased resolution and contrast, as well as better energy efficiency which allows AR hardware to become more viable in business applications.

Real-time data processing is another key factor in determining the effectiveness of AR systems for aviation. AR Systems in Aviation frequently incorporate data from various sources to enrich the user's experience, including aircraft maintenance databases, digital twin models, and aircraft flight management system data. This typically requires advanced processors capable of rendering complex 3D geometry and processing large amounts of data with little-to-no latency (time delay in displaying the data to the user after corresponding user movement). In aviation applications, latency is an important factor; even a small amount of time between when the user moves and when the displayed objects adjust (update) can lead to a misalignment, thereby limiting usability and

possibly creating a safety hazard. Many Aviation AR Systems utilize edge computing architectures, as well as dedicated graphics rendering processors, to provide low-latency (real-time) rendering of digital overlays.How aviation professionals will interact with an augmented reality (AR) system is determined by the user interaction interface (UI). Interaction methods can include gesture recognition, voice commands, eye gaze tracking, and hand-held controllers. In maintenance settings, hands-free interaction is critical since technicians frequently need both their hands for mechanical tasks. Additionally, voice-controlled systems need to perform without error in high noise levels, such as a hangar and gesture systems need to be able to identify intentionally executed gestures and differentiate between motions associated with routine tasks. In the cockpit environment, interaction design should minimize distraction and not conflict with existing instrument control.

III. APPLICATIONS OF AR IN AVIATION

The application of augmented reality (AR) in aviation is changing how this industry works by providing an effective way to enhance all aspects of aviation (e.g., maintenance, training, operations, and safety). By superimposing digital information on top of real objects in the world, AR also allows aviation workers access to immediate, actionable, contextualized data while allowing their work to continue uninterrupted. The following description provides more detail on the main application areas for AR and its impact.

Both MRO operations have complex procedural requirements with extensive technical documentation, and AR applications provide visual representations of everything including the steps to follow; required torque specifications; electrical wiring diagrams; structural schematics, etc., projected directly onto the aircraft components that are being worked on by aircraft mechanics. This way, technicians do not have to go back and forth to paper manuals or external devices (e.g., tablets). Instead, they receive hands-free assistance while working through the use of smart glasses or head-mounted displays. Boeing and Airbus have explored the use of AR-based digital workflow systems in an effort to reduce the total time to complete aircraft inspections and minimize procedural deviations/variances. According to field trials conducted, both maintenance durations and task accuracies were improved due to the use of AR application technology, resulting in definable operational cost savings. In addition to this, AR also allows for predictive maintenance capabilities by integrating real-time sensor data with virtual mirrors (digital twins) in such a manner that aircraft may be identified to have potential component failures before they occur.Along with pilot training and flight simulation being another major use of AR/VR technology, flight training is often facilitated through the use of flight simulators; however, traditional flight simulation devices are expensive and require significant resources (both in equipment and personnel) to utilize effectively.AR technologies enhance flight training by providing the pilot with a combination of a physical cockpit environment along with digital enhancements that depict flight paths, changes in weather, malfunctions of the aircraft systems, and other procedures required to accomplish safe flight operations (such as emergency procedures). Additionally, AR provides the pilot with a combination of both extended reality (virtual reality) and real-world physical control inputs as he/she performs simulated flight tasks. By providing contextual information to the pilot within his/her field of view, AR technology not only enhances the pilot's situational awareness, but also improves the quality of training when developing procedural competencies within the pilot.The use of AR technology for improving situational awareness and real-time decision making while performing flight operations has also gained interest in the aviation community. Examples of AR systems utilized in the aviation industry today include advanced heads-up displays that project navigation cues, visual runway alignments, terrain maps, warnings of potential mid-air collisions, and weather overlays directly into the pilot's line of sight. The goal of these systems is to minimize the pilot's use of head-down instrument scanning and reduce workload at critical points in time (e.g.,

during takeoff and landing) while better informing the pilot of relevant flight status information.Safety management is always a primary consideration for aviation regulatory agencies such as the Federal Aviation Administration (FAA); and because of this, they are continuously reviewing the certification process to ensure that AR technologies used in cockpit systems meet established safety standards. One further compelling use of Remote Expert Collaboration Technology is enabling maintenance technicians equipped with AR enabled smart glasses to transmit live video directly to engineers or other specialist personnel at a different location. Once these experts have a live view of what is happening in front of the technician, they can provide annotations on the technician's field of view, direct the technician visually, and approve procedures, all without needing to be present on-site. This reduces the time that an aircraft is out of service due to maintenance activities, reduces travel costs for maintenance personnel that might have to travel to provide support to the technician, and improves the sharing of knowledge among geographically separated maintenance teams. In addition, AR-assisted remote support has a number of significant operational benefits for regional or remote airports that may not have specialized resources available on location.

IV. CURRENT CHALLENGES
A. Technical Limitations
- o Accurate tracking in varying lighting conditions
- o Display brightness and battery life
- o Latency issues affecting real-time overlays

B. Human Factors and Safety
Improper AR implementation may cause distraction, cognitive overload, or misinterpretation of information, especially in critical flight operations.

C. Regulatory Certification
Aviation authorities require rigorous testing and certification for cockpit technologies, slowing AR adoption in operational aircraft systems.

V. BENEFITS OF AR IN AVIATION
- o Improved maintenance efficiency
- o Enhanced training effectiveness
- o Reduced operational errors
- o Increased situational awareness
- o Cost savings through digital documentation

These benefits explain growing industry interest despite existing challenges.

VI. CONCLUSION
In the aviation industry, augmentation reality (AR) technology is being used to improve aviation operations through areas such as maintenance, training, and operational support, providing benefits of efficiency and safety. However, technical limitations, regulations, and human factors currently inhibit the full-scale use of AR in aviation operations. Continued technological improvement and collaboration between regulators and operators are both required to achieve extensive integration of AR technologies and systems into aviation operations. The use of AR technologies in aviation will likely expand as these challenges are overcome. As aviation systems continue to evolve through increased automation and digitalisation, AR will provide an essential interface for complex aircraft systems and human operators. By providing intuitive visual overlays of complex technical data, AR assists with reducing the cognitive load of operators while improving the accuracy of procedural activity. Measured improvements in speed of inspection, accuracy of documentation, and collaboration in a remote environment have demonstrated the value of using AR within maintenance operations in the aviation industry. AR-based hybrid simulation systems in the training environment provide a scalable and cost-effective solution to the use of traditional full-motion simulators while providing realistic interaction with physical controls.

Aviation is an industry with stringent regulations and certification processes for systems that are considered safety-critical. Regulatory agencies such as the FAA or EASA require that new

systems for avionics technology undergo extensive validation prior to being certified as reliable, robust under environmental conditions and having fail-safe characteristics. For AR to be successfully deployed for flight-critical tasks, it must be able to operate with minimal latency, demonstrate high registration accuracy, provide electromagnetic compatibility and integrate securely with an already established avionics architecture. Validation of the human factors associated with AR will ensure that AR provides situational awareness rather than detracting from it.

VII. REFERENCES

[1] R. T. Azuma, "A survey of augmented reality," *Presence: Teleoperators and Virtual Environments*, vol. 6, no. 4, pp. 355–385, 1997.

[2] S. Henderson and S. Feiner, "Augmented reality for maintenance and repair (ARMAR)," *IEEE Trans. Visualization and Computer Graphics*, vol. 17, no. 10, pp. 1355–1368, Oct. 2011.

[3] P. Milgram and F. Kishino, "A taxonomy of mixed reality visual displays," *IEICE Trans. Information Systems*, vol. E77-D, no. 12, pp. 1321–1329, 1994.

[4] Federal Aviation Administration, *National Aviation Research Plan FY 2024–2028*, Washington, DC, 2023.

[5] X. Zhao, Y. Liu, and H. Wang, "Augmented reality-based aircraft inspection and maintenance: A review," *Computers in Industry*, vol. 149, pp. 103–118, 2023.

[6] M. Billinghurst, A. Clark, and G. Lee, "A survey of augmented reality," *Foundations and Trends in Human–Computer Interaction*, vol. 8, no. 2–3, pp. 73–272, 2015.

[7] L. Lutnyk, J. Gerken, and M. D. Rauterberg, "Context-sensitive AR assistance in the cockpit for emergency handling," *Int. J. Human–Computer Interaction*, vol. 40, no. 3, pp. 412–428, 2024.

[8] A. Sarbach et al., "Evaluating AR navigation aids for situation awareness in pilot cockpits," in *Proc. ACM CHI*, 2025, pp. 1–12.

[9] N. A. Nazri and R. Ahmad, "Implementation of AR in aircraft inspection," *E3S Web Conf.*, vol. 465, 2024.

[10] V. S. Gadow, "AR-based maintenance operations in aerospace," Ph.D. dissertation, Univ. of South Carolina, 2024.

[11] J. Rekimoto, "AR Interfaces for aviation," *IEEE Aerospace and Electronic Systems Magazine*, vol. 38, no. 6, pp. 22–30, Jun. 2023.

[12] C. Zhou, "AR HUDs: Tech review & aviation implications," *Micromachines*, vol. 15, no. 4, pp. 442–460, 2024.

[13] M. R. Endsley, "Situation awareness in aviation systems," *Human Factors*, vol. 37, no. 1, pp. 32–64, 1995.

[14] J. Carmigniani et al., "Augmented reality technologies, systems and applications," *Multimedia Tools and Applications*, vol. 51, no. 1, pp. 341–377, 2011.

[15] Boeing Research & Technology, "Evaluation of AR systems for aircraft maintenance," Boeing Tech. Rep., Seattle, WA, 2023.

[16] D. R. Kearney, T. Heffernan, and R. Walker, "Human factors for wearable AR in aviation," in *Proc. Int. Conf. Human–System Interaction (HSI)*, 2023, pp. 278–285.

[17] A. Zolliker, M. Rachidi, and S. Mann, "AR in aerospace manufacturing," *J. Aerospace Engineering*, vol. 34, no. 8, pp. 1–13, 2021.

[18] S. J. Park and H. S. Kim, "AR-based training for aerospace maintenance," *Int. J. Aerospace Engineering*, vol. 2022, 2022.

[19] P. G. Ryan and K. Hughes, "AR HUD design for aircraft situational awareness," in *Proc. IEEE ISMAR*, 2022, pp. 98–107.

[20] C. Reilly and M. C. Lin, "AR vs. conventional methods in aviation maintenance," *J. Industrial Information Integration*, vol. 27, pp. 100–112, 2023.

[21] S. K. Singh and B. K. S. Chahal, "Augmented reality in pilot training: challenges and advancements," *Int. Journal of Engineering & Technology*, vol. 7, no. 3, pp. 238–245, 2024.

[22] Y. Kim et al., "AR-assisted remote expert support in aircraft maintenance," *Proc. IEEE Intl. Conf. Systems, Man, and Cybernetics*, 2024, pp. 1458–1465.

[23] T. Nguyen and J. Smith, "Performance evaluation of AR interfaces for aircraft inspection

tasks," *IEEE Trans. Human–Machine Systems*, vol. 55, no. 2, pp. 121–130, Feb. 2025.

[24] L. Wang, H. Zhou, and J. Wu, "Wearable AR for aviation training: A usability study," *Journal of Aviation Technology and Engineering*, vol. 11, no. 1, pp. 42–57, 2024.

[25] M. Patel and S. Kapoor, "Cybersecurity implications of AR systems in aviation," *Intl. Journal of Cyber-Physical Systems*, vol. 12, pp. 77–88, 2023.