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The Role of Immersive Technologies in the Design of eVTOL Simulators

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ABSTRACT

As the electric Vertical Take-Off and Landing (eVTOL) aircraft industry advances, the development of high-fidelity simulators becomes crucial to support pilot training, operational safety, and the integration of eVTOLs into urban air mobility (UAM) ecosystems. This paper explores the transformative role of immersive technologies—such as virtual reality (VR), augmented reality (AR), mixed reality (MR), and Simulated Air Traffic Control Environments (SATCE)—in the design and development of eVTOL simulators, focusing on the convergence of human factors and cutting-edge technological innovation. Combined with SATCE, immersive technologies enable realistic, dynamic training environments that simulate the unique flight characteristics and control interfaces of eVTOLs. SATCE, developed by companies like ASTi, U.S.A., provides a sophisticated simulation of air traffic control (ATC) interactions, allowing pilots to practice real-time communication and decision-making under complex traffic and airspace scenarios. This technology helps bridge the gap between traditional aircraft training and the distinct challenges posed by eVTOL operations in dense urban environments, enhancing pilot situational awareness and decision-making in highly dynamic and unpredictable contexts. This paper examines key case studies where VR, MR, AR, and SATCE have been applied in aviation training, including the implementation of SATCE systems by ASTi and the work of FAST-Group Aero in Germany, who have led the integration of immersive technologies into eVTOL and UAM simulator environments. These examples demonstrate how artificial intelligence-driven communication and immersive simulation transform eVTOL pilot training by offering a comprehensive training experience encompassing technical flight skills and communication with air traffic control, particularly in managing vertical lift, multi-axis control, and navigation through complex urban airspace. Additionally, we explore future trends in immersive technology and its applications in eVTOL simulator design, emphasizing creating adaptable, scalable solutions that align with evolving regulatory frameworks. As UAM continues to grow, there is an increasing need to address the human factors challenges of eVTOL operations, such as pilot workload, human-machine interaction, and emergency scenario management. Integrating immersive technologies and SATCE offers a significant opportunity to optimize these aspects, providing a safe, controlled, and engaging training environment. In conclusion, this paper proposes a human-centric approach to eVTOL simulator design, where immersive technologies and SATCE systems not only replicate real-world complexities but also enhance the learning experience, paving the way for safer and more efficient integration of eVTOLs into the airspace.

Keywords: Artificial intelligence, Simulated air traffic control environment (SATCE), Urban air mobility (UAM), Advanced air mobility (AAM), Virtual reality (VR), Augmented reality (AR), Mixed reality (MR), Electric vertical take off landing eVTOL

INTRODUCTION

The electric Vertical Take-Off and Landing (eVTOL) industry has introduced significant changes in the urban air mobility (UAM) landscape. eVTOL aircraft are expected to provide efficient, sustainable solutions to urban transport challenges, whereas their distinct flight characteristics, navigation dynamics, and operating environments call for advanced pilot training methodologies. To equip pilots effectively for these new operational difficulties, high-fidelity simulators that incorporate immersive technologies such as Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) are essential (Ziakkas et al., 2024a).

Immersive technologies such as digital twins, VR, AR, and MR offer significant potential to improve the design and efficacy of eVTOL simulators (Pinon Fischer et al., 2022). By providing highly realistic and interactive training environments, immersive technologies enable pilots to experience and respond to real-time operational scenarios, improving their situational awareness and decision-making skills. These systems allow pilots to train in dynamic, realistic environments to interact with complex air traffic control (ATC) scenarios, handle emergencies, and navigate complex urban landscapes. Moreover, Simulated Air Traffic Control Environments (SATCE), developed by ASTi, integrate ATC interactions into the training environment, enabling pilots to practice real-time communication and decision-making under high-pressure conditions (ASTi, n.d). As the UAM and eVTOL sectors evolve, addressing human factors such as pilot workload, human-machine interaction, and emergency scenario management becomes increasingly important. Combined with SATCE, immersive technologies help bridge the gap between traditional flight training and the challenges posed by eVTOL operations in dense urban environments (van't Hoff et al., 2022). This paper explores the role of these technologies in enhancing eVTOL pilot training and examines how they can be integrated into simulator designs that align with evolving regulatory frameworks.

Finally, the aim of this paper is to explore the role of immersive technologies in enhancing eVTOL simulator design, with a comparative focus on the regulatory frameworks provided by the European Union Aviation Safety Agency (EASA) and the Federal Aviation Administration (FAA). By examining these regulatory bodies' different approaches to integrating immersive technologies into pilot training, we can better understand the global trajectory of UAM safety and operational efficiency (EASA, 2023).

METHODOLOGY

This research adopted a methodology consistent with Saunders' research onion framework, following a systematic and thorough approach (Saunders et al., 2019). A pragmatic philosophy underpins the research, emphasizing the need to apply practical solutions to the technological challenges in eVTOL training. Additionally, the research utilizes a deductive approach, testing established theories of immersive technologies and simulator design within eVTOL and UAM pilot training. The methodology strategy employs a mixed-methods approach, integrating qualitative case studies with quantitative performance data from simulation training programs (Table 1).

Table 1. Research methodology overview.

Methodology (Research Onion)	Description
Philosophy	*Pragmatism:* This research adopts a practical approach, utilizing the most suitable methods to address the research questions.
Approach	*Deductive:* The study tests theories and hypotheses about using immersive technologies in eVTOL simulators and applies them to specific contexts.
Strategies	*Mixed Methods:* Combines qualitative and quantitative methods to gather broad and deep insights. This includes case studies to explore the application of immersive technologies in detail and quantitative data to measure their impact on pilot training outcomes.
Methods	*Multi-method:* Involves collecting data through various methods such as documentary analysis, interviews, and surveys.
Time Horizon	*Cross-sectional:* Data are collected at a particular time to assess the current state of immersive technologies in eVTOL pilot training.
Data Collection	Conducted through documentary analysis, case studies, and literature reviews. Sources include academic databases like Google Scholar and Web of Science, industry reports, and regulatory documents from ICAO, IATA, FAA, and EASA (2015-2024).
Data Analysis	*Thematic Analysis:* Identifies themes and patterns within the data relating to the integration of immersive technologies, human factors, and regulatory compliance in eVTOL simulator training.

Data collection involves an in-depth analysis of case studies from industry leaders like ASTi, FAST, and regulatory documents from EASA and FAA. The research sources include academic literature from Google Scholar, industry white papers, and regulatory publications. The data collection methods include documentary analysis, case studies, and literature reviews from sources such as the International Civil Aviation Organization (ICAO), International Air Transportation Association (IATA), FAA, and EASA, as well as academic databases like Google Scholar and Web of Science.

The data analysis follows a thematic approach, where the key themes of immersive technology integration, human factors, and simulator design are identified and analyzed across multiple case studies. Ethical considerations were addressed by ensuring the confidentiality of proprietary data and adhering to Purdue University's ethical research guidelines.

Finally, the literature review examines the role of immersive technologies in aviation training, focusing on their application to eVTOL simulators. Previous studies have shown that VR, AR, and MR. are highly effective in creating realistic training environments that enhance situational awareness and decision-making (Pedrioli et al., 2024). Moreover, integrating SATCE into simulators has proven critical in preparing pilots to handle real-time communication with ATC under complex urban airspace scenarios (ASTi, n.d.). Regulatory frameworks established by FAA and EASA underscore the significance of simulator training in aviation safety and the increasing necessity for regulatory harmonization as eVTOL operations proliferate. These organizations have begun to explore how immersive technologies can be integrated into eVTOL training programs, recognizing their potential to improve pilot readiness and safety (FAA, 2024; EASA, 2024).

RESULTS

The adoption of immersive technologies such as VR, AR, and MR in aviation training is well-documented. These technologies have transformed traditional flight simulation by offering interactive, realistic environments that allow pilots to safely engage in complex, real-world scenarios. In the context of eVTOL aircraft, immersive technologies are essential for addressing the unique flight characteristics, multi-axis control systems, and operational environments that pilots will encounter, particularly in UAM ecosystems.

The inclusion criteria for the literature review were as follows:

- Date of Publication: Articles published between 2015 and 2024 to ensure that the research is relevant to current technological advancements and regulatory developments.
- "Augmented Reality," "Mixed Reality," "Simulated Air Traffic Control Environments (SATCE)," "eVTOL," "Urban Air Mobility," "human factors," and "aviation training."
- Source Type: Peer-reviewed journal articles, regulatory white papers, conference proceedings, and case studies related to aviation safety and training.
- Regulatory Focus: Articles specifically addressing or referencing regulations by aviation bodies like the EASA and the FAA were prioritized.

The research exclusion criteria were as follows:

- Studies not related to immersive technology applications in aviation.
- Articles predating 2015, unless cited as foundational to the evolution of aviation training technologies – related to regulations.
- Papers without direct relevance to eVTOL, UAM, or pilot training environments.

From an initial search of over 206 papers, 127 papers were selected for the first screening based on relevance to immersive technologies in aviation. After further refinement, 53 papers were identified as directly addressing eVTOL, UAM, or regulatory frameworks related to training simulators. These final selections form the basis of the thematic research review and analysis as follows:

Application of Immersive Technologies in eVTOL Training

VR, AR, and MR technologies have proven effective in creating highly interactive environments that simulate real-world flight operations (EASA, 2023). The research highlights their ability to replicate scenarios that would otherwise be difficult or impossible to experience in traditional training settings, such as navigating congested urban airspaces or managing sudden mechanical failures during vertical take-offs or landings. For instance, VR enables pilots to immerse themselves in complex, high-pressure environments without the risks associated with real-life operations. AR can overlay crucial information such as flight data, navigation markers, and ATC communications directly onto the pilot's view, improving situational awareness and reducing cognitive load during high-stress situations. MR combines elements of both VR and AR, allowing pilots to interact with physical controls while engaging in a simulated flight environment (Ziakkas et al., 2024a).

SATCE

Simulated Air Traffic Control Environments add critical realism to these immersive simulations. By incorporating real-time ATC communication, SATCE systems allow pilots to practice complex decision-making and communication in scenarios involving dense urban traffic and rapidly changing airspace conditions. Integrating SATCE into eVTOL simulators is particularly valuable, reflecting the communication and coordination challenges pilots will face in the evolving UAM ecosystem (ASTi, n.d).

Human Factors in eVTOL Training Simulators

The human factors component in aviation training is vital in the context of eVTOL operations. Both EASA and FAA highlight the role of cognitive load, situational awareness, and pilot decision-making in maintaining operational safety. The literature shows that immersive technologies are highly effective in simulating high-stress environments where these human factors are tested. EASA's Special Condition VTOL explicitly outlines the importance of incorporating human factors into eVTOL simulator design (EASA, 2024). Pilots must be trained to manage the unique control systems of eVTOL aircraft, which differ significantly from traditional rotorcraft and fixed-wing aircraft. This includes vertical lift operations, multi-axis control, and navigation through dense urban landscapes (Pedrioli et al., 2024). The FAA's UAM Concept of Operations also emphasizes the need for immersive training environments focusing on human-machine interaction. The FAA's guidelines support a gradual implementation of immersive technologies that improve pilot performance by addressing workload management, situational awareness, and the ability to make rapid decisions in response to changing airspace conditions (FAA, 2024).

The integration of immersive technologies such as VR, AR, and MR into eVTOL simulators is significantly influenced by regulatory frameworks, particularly those set by EASA (EASA, 2023). These frameworks guide how immersive technologies are employed in simulators to meet the stringent safety and operational requirements for eVTOL pilots, ensuring they can manage the complex demands of UAM (EASA, 2024).

EASA's Special Condition VTOL

EASA developed the Special Condition VTOL framework to address the unique design and operational challenges posed by eVTOL aircraft, which differ from traditional rotorcraft and fixed-wing aircraft. The EASA's special condition framework provides a comprehensive set of airworthiness standards for eVTOL aircraft, particularly those in the small category with vertical take-off and landing capabilities under the certification phase. These standards ensure that the safety and design objectives for eVTOL aircraft are not limited by traditional design specifications, integrating immersive technologies, which allows for innovation while maintaining safety (EASA, 2024). Combined with simulators, immersive technologies offer a flexible and effective way to meet EASA's Special Condition VTOL requirements. Through VR, AR, and MR, simulators can replicate realistic urban flight scenarios, complex vertical lift operations, and emergency procedures, all critical to the certification process (Ziakkas et al., 2023b).

Pilot Training and Human Factors in eVTOL Operations

A key finding from the EASA guidelines is the emphasis on human factors in designing and operating eVTOL aircraft. EASA's Means of Compliance (MOC) document highlights the importance of pilot workload, situational awareness, and decision-making capabilities, all addressed through immersive simulation environments. EASA's MOC VTOL.2000 specifies the need for simulations that reflect the aircraft's mass and center of gravity characteristics. Simulators equipped with immersive technologies can replicate these physical dynamics in real-time, allowing pilots to experience the challenges of controlling an eVTOL aircraft under different conditions (EASA, 2024). Moreover, EASA emphasizes training in emergency scenarios, such as loss of lift or propulsion during take-off or landing. Immersive technologies allow pilots to practice managing these scenarios within a controlled, risk-free environment, improving their ability to respond to real-life emergencies. By incorporating immersive technologies into the training process, pilots can practice high-stress decision-making and refine their response to complex, multi-axis control systems inherent in eVTOL aircraft (Ziakkas et al., 2023a). FAST-Group Aero in Germany has been at the forefront of utilizing immersive technologies to enhance the design and functionality of eVTOL simulators, playing a critical role in advancing pilot training for UAM. By integrating VR, AR, and MR technologies into their simulation platforms, FAST-Group Aero offers pilots the opportunity to experience realistic, high-fidelity flight scenarios that mimic the unique dynamics of eVTOL aircraft. The immersive environments provide pilots with unparalleled situational awareness, allowing them to safely practice flight operations that would be difficult to recreate in traditional simulators (FAST, 2024).

SATCE

One of the standout immersive technologies discussed in this paper is SATCE, which is crucial for preparing eVTOL pilots for operations in busy urban airspaces, focusing on communication competency. EASA's regulations highlight the importance of effective communication between pilots and ATC, particularly in congested urban environments where eVTOL aircraft will operate in close proximity to each other and other airborne vehicles. Including SATCE in pilot training aligns with EASA's MOC VTOL.2500, which addresses flight guidance systems and workload alleviation for pilots (EASA, 2024). By reducing the workload associated with ATC communication and improving situational awareness, SATCE enhances flight safety and efficiency in eVTOL operations (EASA, 2023). SATCE systems integrated into eVTOL simulators provide a dynamic training environment where pilots can practice real-time communication with ATC, manage complex airspace scenarios, and navigate safely through urban landscapes. In these simulations, pilots are required to respond to rapidly changing airspace conditions, such as sudden weather changes or the appearance of obstacles, while maintaining communication with ATC. The system also provides feedback on pilot performance, allowing for continuous improvement and adaptation to the specific demands of eVTOL flight. The findings of human factors and immersive technologies implementation in eVTOL are summarised in Table 2.

Table 2. Literature review findings.

Aspect	EASA Perspective	FAA Perspective
Simulator Requirements	EASA mandates comprehensive simulation environments replicating real-world complexities, emphasizing human factors (Pedrioli et al., 2024).	FAA employs a phased approach, allowing for gradual complexity in simulator design as UAM evolves (FAA, 2024).
Immersive Technology Integration	EASA requires simulators' VR, AR, and MR technologies to replicate eVTOL flight characteristics and control dynamics (EASA, 2023).	FAA supports immersive technologies but allows flexibility in their implementation based on industry readiness (FAA, 2024).
Human Factors Focus	EASA prioritizes pilot workload, situational awareness, and decision-making in high-pressure environments (Pedrioli et al., 2024).	FAA emphasizes the scalability and adaptability of simulator technologies to accommodate evolving UAM operations (FAA, 2024).
ATC Communication	EASA requires SATCE integration to simulate real-time ATC communication in urban environments (Pedrioli et al., 2024).	FAA allows for gradual integration of SATCE, supporting a crawl-walk-run model of UAM operations (FAA, 2024).

The research further focuses on the role of safety testing and structural compliance in eVTOL certification, specifically in MOC VTOL.2235, which addresses structural strength and deformation. Immersive simulators provide a valuable tool for testing and validating these structural requirements by allowing pilots to train in environments that simulate high-stress flight conditions, such as high winds, extreme temperatures, and rapid altitude changes. Simulating these conditions in a virtual environment ensures that pilots are adequately prepared for real-world operations, meeting the safety and performance standards set by EASA (EASA, 2024).

Additionally, per the extended literature review - immersive technologies contribute to meeting EASA's expectations for flight performance data, as outlined in MOC VTOL.2105. By simulating performance data under different environmental conditions, immersive simulators help validate an aircraft's operational limits, ensuring it complies with the necessary airworthiness standards. This includes testing performance in take-off and landing scenarios, climb and descent rates, and the energy consumption of the aircraft's propulsion systems (EASA, 2023). The findings of safety testing and structural compliance in eVTOL certification are summarised in Table 3.

Table 3. Certification literature review findings.

Immersive Technology	Application in eVTOL Simulators	EASA's Compliance (MOC)	Key Benefits
Virtual Reality (VR)	Simulates complex urban airspace environments and multi-axis control systems.	MOC VTOL.2100 (Mass and CG), MOC VTOL.2105 (Performance Data)	Enhances situational awareness and decision-making in dense airspaces.
Augmented Reality (AR)	Provides real-time overlays for ATC communication and navigation.	MOC VTOL.2500 (Flight Guidance Systems), MOC VTOL.2005	It improves pilot-ATC coordination and reduces communication errors.
Mixed Reality (MR)	Combines real-world elements with simulated data to practice emergency procedures.	MOC VTOL.2235 (Structural Strength), MOC VTOL.2400 (Lift/Thrust Systems)	It enables pilots to train for emergency scenarios in a realistic yet controlled environment.

CONCLUSION

Immersive technologies are expected to play a critical role in the future of eVTOL pilot training. The combination of VR, AR, MR, and SATCE with regulatory frameworks like those from EASA ensures that training programs are technologically advanced and compliant with international safety standards. The scalability of these solutions means that they can be adapted to the evolving UAM landscape, contributing to the safe and efficient integration of eVTOL aircraft into urban airspaces. The findings from this study underscore the importance of continued research and collaboration between technology developers, aviation authorities, and industry stakeholders to ensure that eVTOL pilot training remains at the cutting edge of technological innovation and regulatory compliance.

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