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Advancing Aviation Workforce Development Through Immersive Technology: A Virtual Reality Framework for UAS Pilot Education and Skill Practice

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INTRODUCTION

Unmanned Aircraft Systems (UAS) have emerged as an essential component within the evolving landscape of smart cities and advanced air mobility. UAS are increasingly transforming how industrial tasks are performed across sectors such as agriculture, construction, infrastructure inspection, logistics, and smart city operations [1]. Compared to traditional methods, UAS offer improved efficiency, reduced operational costs, and enhanced safety, enabling applications including traffic management, cargo delivery, environmental monitoring, and security [1]. In infrastructure inspection, UAS deployment has reduced traffic disruptions and reliance on heavy equipment, with reported cost reductions of up to 74% in bridge inspection operations [2], [3]. Similar benefits have been observed in tunnel, penstock, transmission line, and railway inspections, where UAS minimize human exposure to hazardous environments while improving inspection coverage and efficiency [4]-[6]. As UAS operations become increasingly embedded in commercial and public domains, there is a parallel need to prepare a new generation of pilots capable of navigating complex operational environments while adhering to evolving regulatory and safety standards.

This paper establishes a framework for developing a Virtual Reality (VR)-based UAS pilot training model that integrates accessibility, affordability, and safety within aviation education. The framework addresses a critical gap in current training paradigms, which often require significant physical resources, specialized facilities, and access to aircraft – barriers that limit institutional capacity and student participation, particularly at the K–12 and undergraduate levels. VR technology offers a unique opportunity to simulate realistic drone operation scenarios providing a cost-effective, immersive approach to UAS training, enabling K-12 and higher education institutions with limited resources to offer hands-on experience to a broader range of students without the need for physical drones. This approach enables learners to practice essential skills and safety protocols, fundamental flight maneuvers, and situational awareness in a virtual setting, mitigating the risks and costs associated with inexperience.

This paper highlights the development of the proposed VR-based drone maneuvering learning framework and its direct alignment with the Federal Aviation Administration (FAA) Part 107 Remote Pilot Certificate curriculum, supplementing the Part 107 lessons with hands-on VR drone flying experience. Overall, this paper aims to contribute to the growing discourse on technology-enhanced aviation education – it provides an overview of the first steps taken to advance drone education and hands-on drone maneuvering experience that is immersive and engaging for learners, aligned with industry requirements, and scalable for specific operational environment and application.

BACKGROUND AND RELATED WORK

This section presents a brief overview of the current practices associated with the utilization of VR technology as a component of digital educational experiences to prepare students for various opportunities in the smart mobility world. This section establishes the applications of VR in training and education, uses of VR and UAS in smart cities, and applications of VR in UAS training.

UAS Systems in Smart Cities: Rapid integration of UAS across industries – spanning agriculture, logistics, emergency response, and environmental monitoring – demonstrates the transformative potential of this technology. While UAS are becoming increasingly capable of autonomous operations, a common operational requirement across many diverse industrial applications is the pilot's ability to accurately track, follow, and maneuver relative to target objects – skills that require substantial practice and refinement. These skills are critical particularly in complex, dynamic, or safety-critical environments [7], and UAS pilots may often require additional domain-specific training to operate effectively within such contexts [8]. However, in the U.S., regulatory requirements for UAS pilots under Federal Aviation Administration (FAA) Part 107 focus primarily on passing a written knowledge examination, with no mandatory hands-on flight training required for certification [9]. While waivers may permit advanced operations such as beyond visual line-of-sight flight [10], opportunities for real-world UAS flight training remain constrained by safety risks, regulatory limitations, and operational costs [11], [12]. Virtual Reality (VR) has emerged as a promising approach to address this gap by enabling immersive, customizable, and risk-free training environments.

VR in Training and Education: Virtual Reality comprises a range of technologies that are used to help users realize a simulated environment and experience – typically this involves the utilization of software, a computer, and other devices such as a head-mounted-display (HMD) [13]. VR technology is one of several immersive technologies currently being utilized in training environments, utilizing its gamification and simulation capabilities to train various types of operators [14]. VR technology has the potential to facilitate knowledge transfer in students and provide them with an experiential and engaging aspect of education, helping students learn better, develop literacy skills, and gain interest and motivation [15]. Numerous studies have highlighted the benefits of utilizing VR technology in educational settings, especially in a combination with traditional methods. For instance, Sanzana et al. [16] indicated that when VR technology is combined with traditional teaching methods, there were notables increases in skill development, memory, and knowledge retention. Bertram et al. [17] utilized a VR environment to train police personnel on complex joint assignments and found that VR technology is as good as traditional methods of learning, and also showed that VR technology could be utilized to prepare police personnel for tasks that would be hard to train for in real-world environments.

Another benefit of utilizing VR technology in training has been the safety of the trainees [14]. In settings like the construction industry, VR technology has been noted to help trainees improve their performance of tasks and retain acquired knowledge [14]. As such, VR technology provides users with the opportunity to learn about various failure potentials without experiencing life-threatening dangers [18]. VR technology has been noted as a potential tool to facilitate safety training without endangering the lives of the workers in highly hazardous industrial sectors [19]. Additionally, VR technology utilization is viewed as a means of minimizing the overall cost of training in such industries. For instance, in the US Air Force, incorporating VR in aircraft maintenance training of the C-130 aircraft minimizes the amount of time real-world aircraft have to stay in the hangar for training purposes [20]. VR technology has shown its effectiveness in training and education due to its potential for minimizing risk and operational costs [15]. By utilizing VR technology in UAS pilot training, it is possible to customize various operational parameters such as wind speed, flight mode, or endurance hence greater control in numerous variables [7]. As such, VR represents a scalable and flexible solution for developing UAS pilot proficiency within existing regulatory and safety constraints.

Scope of this Paper: Given the cost-effectiveness of the technology, application of VR in UAS training may provide a platform to the students for learning and mastering the fundamental drone maneuvering in a virtual environment – safe and cost effective. Since the ultimate goal is for the students to master UAS flight skills in real-world conditions, VR-based knowledge may serve as a sustainable learning progression for students before they can fly a real UAS. While several UAS simulator training toolkits have been developed to provide specific and advanced simulation scenarios such as inspection of bridges, power lines, towers, wind turbines, and solar panels [21], there are no available VR-based educational toolkits for K-12 students that provide a platform for them to learn and practice basic drone maneuvering, flight, and operational skills in a safe and risk-free environment and that could supplement the FAA Part 107 education by providing realistic visuals to learn complex ideas.

VR-BASED UAS TRAINING FRAMEWORK ARCHITECTURE

This study presents the architectural framework developed to introduce K–12 and higher education students to UAS operations and Part 107 knowledge through a safe, risk-free, and cost-effective virtual environment. The project is supported by a state Department of Transportation grant aimed at leveraging immersive technologies to expand STEAM (Science, Technology, Engineering, Art, and Math) learning and career exploration in emerging mobility domains. A central objective of the grant is developing scalable *educator toolkit* to address an identified gap of limited/no access to digital experiences. Therefore, the goal of the State funded research grant was to identify, design and potentially test engaging and educational digital experiences that introduce K-12 and higher education students to the world of smart mobility technologies and career opportunities.

To meet this goal, a research team at Bowling Green State University (BGSU) School of Aviation developed the **Project VISTA** proposal, structured around three interdependent dimensions of the state DOT's RFP: Future of Transportation, Technology Application, and Education.

- **Future of Transportation:** This dimension anchors the framework within the evolving smart mobility ecosystem shaped by electrification, automation, connectivity, and emerging aerial platforms. Areas of interest include electric vehicles, automated and connected vehicle systems, drones, and electric air vehicles. This domain defines the operational and infrastructural context in which future transportation professionals will be expected to work, including considerations related to safety, integration, sustainability, and system complexity.
- **Technology Application:** This dimension emphasizes the use of advanced digital tools to support engagement, exploration, and experiential learning in transportation-related contexts. Examples include immersive and interactive technologies such as Virtual Reality (VR), Augmented Reality (AR), and 360-degree virtual environments. The focus is on leveraging digital platforms to make emerging transportation concepts tangible and accessible to learners.
- **K-12 and Higher Education:** This dimension highlights the importance of educational experiences that span multiple learning levels and support early exposure to transportation and mobility-related careers. The intent is to broaden participation, promote equity and accessibility, and strengthen the pipeline of students prepared to engage with future transportation challenges.

In ProjectVISTA architecture, rather than treating these three dimensions as independent pillars, the authors used them to define a bounded design space whose convergence guides both the pedagogical and technical architecture of the framework. The value of the framework emerges through the interaction of these domains rather than from any single dimension alone.

- **Future of Transportation × Technology Application** defines the simulation layer: immersive environments that model emerging mobility systems (e.g., UAS operations) to examine operational procedures, infrastructure interactions, and safety constraints.
- **Technology Application × Education** defines the pedagogical layer: structured integration of immersive tools into formal and informal learning contexts to support conceptual understanding, systems thinking, and skill acquisition.
- **Education × Future of Transportation** defines the future workforce layer: curricular exposure to next-generation smart mobility systems aligned with evolving aviation industry roles and diverse competencies.

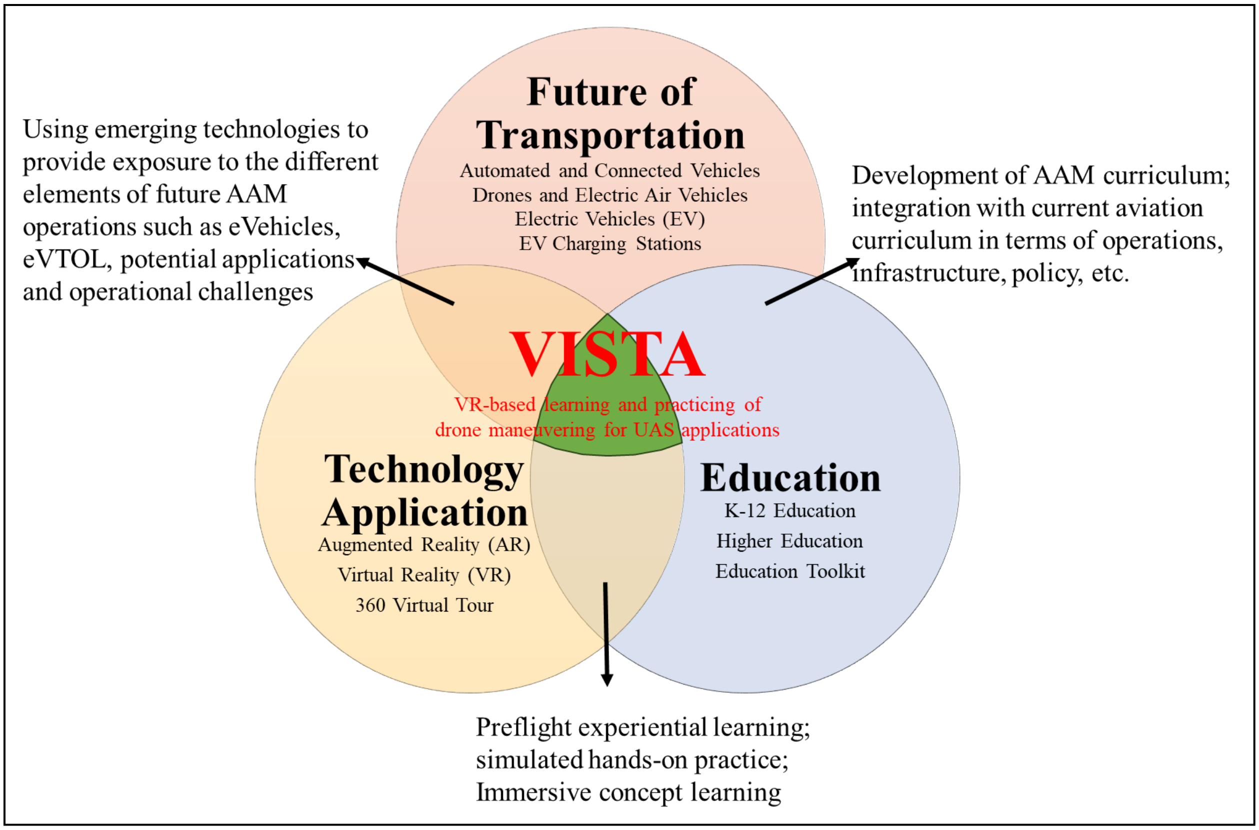

Figure 1. Research ProjectVISTA addresses the intersection of the need to expose K-12 and higher education students to the future of transportation such as smart mobility and cities through emerging technologies such as AR/VR.

At the convergence of all three domains lies **Project VISTA**, which operationalizes immersive simulation as a structured educational platform for introducing students to UAS operations, fundamental maneuvers, and supplement FAA Part 107 knowledge areas. The aim of Project VISTA is to engage students in guided flight tasks – such as basic maneuvering, airspace awareness, and operational decision-making – inside a controlled virtual environment that embeds safety constraints, regulatory considerations, and procedural logic. This integration ensures that VR technology functions not as a standalone visualization tool, but as a pedagogically grounded learning aid that reinforces topic understanding and early skill development. By maintaining modular scenario design and educator-ready deployment, Project VISTA framework supports scalability across K–12 outreach, introductory aviation courses, and workforce development initiatives, while preserving safety, cost-efficiency, and accessibility.

To operationalize the conceptual framework, Project VISTA was implemented through three structured objectives aligned with the technical progression of the project:

- **Objective 1: Mapping of the Part 107 Curriculum to Identify VR Opportunities**
    - Systematic analysis of FAA Part 107 knowledge domains to identify instructional gaps and experiential limitations.

    - VR opportunity mapping to determine which topics (e.g., airspace awareness, operational procedures, risk considerations) could be meaningfully translated into immersive environments.
- **Objective 2: VR Scenario Development and Simulation Integration**
    - Development of VR-based modules aligned with selected Part 107 topics.
    - Design and implementation of basic drone maneuvering simulations within a controlled virtual environment to support foundational flight skills.
    - Expansion of VR environments into application-specific UAS operations scenarios (time and resources permitting).
- **Objective 3: Testing, Evaluation, and Iterative Refinement**
    - Pilot testing of the VR training toolkit with students to document usability, engagement, and instructional effectiveness.
    - Iterative optimization of scenarios and instructional materials based on observed performance and structured feedback.

VR TRAINING MODULE STRUCTURE AND TOPIC GROUPS

While the broader Project VISTA framework encompasses curriculum mapping (Obj.1), immersive environment design (Obj.2), and iterative validation (Obj.3), the scope of this paper is limited to briefly discussing the preliminary instructional modules and the respective sub-topics identified during these processes. Specifically, the scope of this paper is primarily positioned between the objectives 1 and 2 of the larger Project VISTA research, with the goal of providing an overview of the overall instructional modules. As such, following the systematic analysis of the FAA Part 107 curriculum and VR opportunity identification, selected knowledge domains were consolidated into five instructional modules, and a Module 0 for foundational drone maneuvering practice. The modules briefly described in this paper define the topic areas that are targeted for immersive VR scenario development in the current phase of the project. Figure 2 provides an overview of each of the modules.

<u>Module 0 - Basic Drone Maneuvers:</u> This is the entry level module and serves as the foundational drone flight-skills practice space. Students first learn basic drone control in a low-risk VR environment before moving into more complex operational scenarios.

<u>Module 1 - Airspace Classification and Special Use Areas:</u> This module introduces the regulatory and navigational side of UAS operations and help students connect abstract FAA airspace concepts to practical UAS operating decisions. Specifically, this module is designed for students to visualize airspaces, understand airspace classifications, authorization requirements, and operational decision-making.

<u>Module 2 - Effects of Weather on UAS and Payload:</u> This module focuses on environmental constraints on drone operations. This module exposes the students to wind, gust, precipitation, and visibility challenges of drone operations, and the related fly-no-fly

decision-making. The module helps learners understand that safe UAS operation depends on environmental assessment.

Module 3 - Drone Emergency Procedures and Preflight: This module shifts from normal operations to provide exposure to abnormal and emergency operations such as lost link, GPS failure, Low battery return-to-home, and preflight inspection scenarios. The overall goal is to develop procedural thinking and safety judgment.

Module 4 - Scenario-Based Basic and Multi-Rotor Application Missions: This module serves as the "capstone" of the core Project VISTA training sequence and integrates the earlier modules into realistic mission scenarios. Students will apply basic maneuvering, airspace awareness, weather judgment, and emergency procedures inside operationally meaningful tasks.

**Module 5 - Industry-Driven Applications: This module represents the next phase beyond the original VISTA scope into application-specific UAS workforce training.

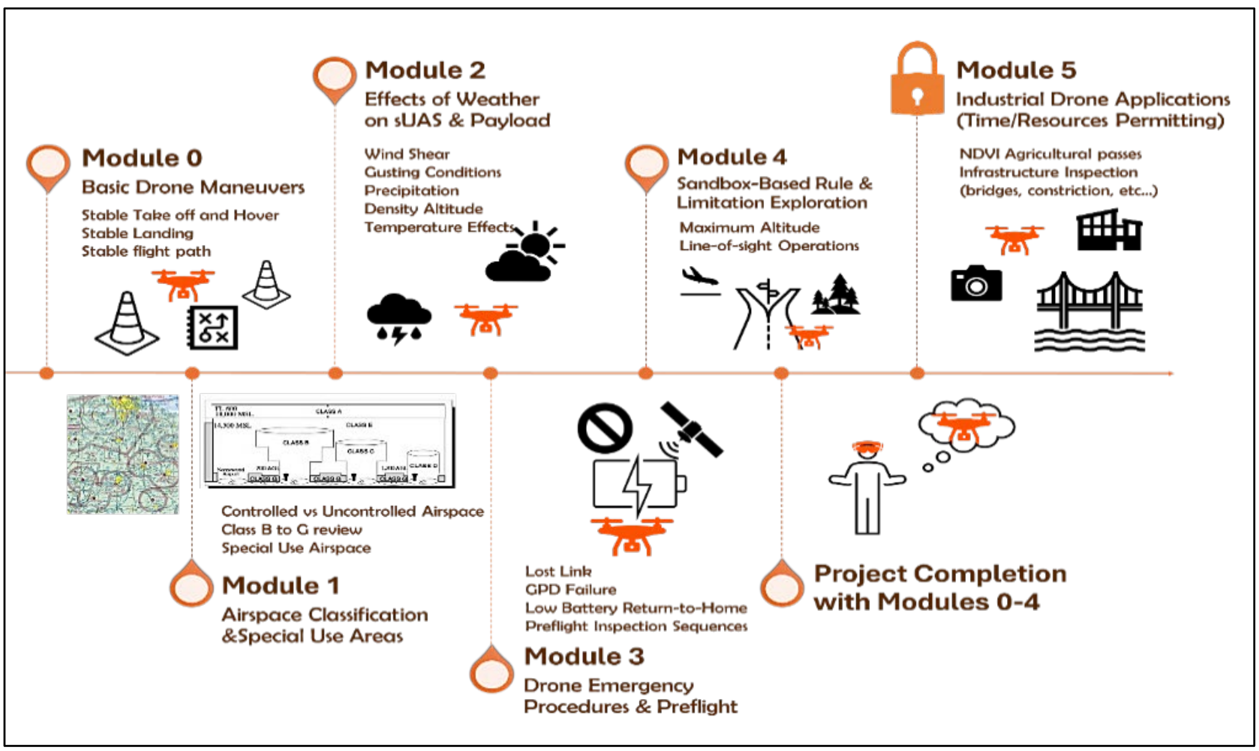

Figure 2. Overview of Project VISTA Modules and the VR Lessons Development

EDUCATIONAL IMPLICATIONS, DISCUSSION, AND CONCLUSION

The framework presented in this paper addresses an important workforce challenge associated with the rapid expansion of Unmanned Aircraft Systems (UAS) across smart mobility and smart city ecosystems. As UAS adoption accelerates, the availability of a sufficiently trained and licensed workforce has emerged as a limiting factor in realizing the full potential of these systems. This paper presented the conceptual architecture and instructional structuring of Project VISTA, a VR-based UAS training framework designed to align FAA Part 107 knowledge domains with immersive learning modules. Through systematic curriculum mapping and VR opportunity identification, five sequenced instructional modules were defined to support foundational flight skills, regulatory awareness, environmental considerations, and safety decision-making within a controlled virtual environment.

From an educational perspective, immersive VR-based UAS training offers potential advantages in accessibility, safety, and cost efficiency. Traditional hands-on drone training requires investment in aircraft, supporting equipment, suitable training spaces, and instructor oversight, while also introducing safety risks during early skill acquisition when novice operators may be more likely to lose control or make operational errors. A cost-effective VR-based training environment can help mitigate some of these challenges by allowing students to practice foundational flight skills, procedural knowledge, and safety-related decision-making in a controlled setting before operating physical aircraft. This capability may be particularly valuable for K–12 and higher education institutions with limited resources, where access to physical UAS equipment, flight space, and trained instructors may constrain experiential learning opportunities.

The modular structure of Project VISTA also supports instructional flexibility. The framework progresses from basic drone maneuvers to airspace classification, weather effects, emergency procedures, and scenario-based mission practice. This progression allows instructors to introduce UAS concepts in a scaffolded manner while connecting technical knowledge to operational decision-making. The adaptability of VR further supports a wide range of instructional contexts, from basic maneuvering and control to application-specific scenarios such as aerial surveying or emergency response. Repeated practice in immersive environments facilitates skill acquisition and retention, while built-in performance tracking enables data-informed assessment of learner progress. These features may support targeted instruction and align with competency-based training approaches increasingly emphasized in aviation and engineering education.

From a workforce perspective, Project VISTA contributes to long-term workforce development by exposing students to emerging transportation technologies and associated career pathways at an early stage. By aligning immersive simulation with regulatory knowledge and authentic operational contexts, the framework helps students connect technical concepts to real-world practice while supporting technological literacy and STEM engagement. The scalability of VR platforms further enables broader institutional adoption without significant infrastructure investment, supporting sustained workforce readiness. While this paper focused on the framework and instructional module structuring, ongoing work includes continued scenario refinement and evaluation to assess instructional effectiveness. As such, the framework should be viewed as a foundation for future implementation and evaluation rather than evidence of instructional effectiveness. Collectively, Project VISTA demonstrates how immersive technologies can be intentionally integrated into aviation education to support safe, scalable, and workforce-aligned training pathways.

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