Immersive Learning Environment Design of Outdoor Education Space Using Artificial Intelligence Augmented Reality Technology

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***Abstract*—This study presents a technically grounded design and implementation of an AI- and AR-enabled immersive learning environment for outdoor education. Moving beyond conceptual descriptions, the study develops an executable system framework that integrates adaptive navigation and positioning, context-aware virtual tours, task-driven scenario simulation, and real-time feedback mechanisms. Each functional module is explicitly linked to algorithmic implementations, including multi-sensor state estimation, constrained generative scene construction, and reinforcement-based adaptive control, enabling reproducible system behavior in real outdoor settings. A controlled field experiment was conducted using an experimental group and a control group under identical instructional conditions. Quantitative evaluation based on pre–post testing, behavioral logging, and statistical analysis demonstrates that the proposed system achieves statistically significant improvements in learning interest, participation, knowledge mastery, and problem-solving ability. Experimental conditions, data characteristics, and methodological limitations are explicitly reported to support result verification and generalizability. The findings indicate that the proposed immersive learning environment constitutes a validated system-level contribution rather than a purely conceptual framework, offering practical and scientific value for computer science–oriented educational technology research.**

Keywords*—Artificial intelligence; augmented reality; outdoor education space; immersive learning environment; system-level evaluation

I. Introduction

With the accelerated development of globalization and informatization, the education industry is facing unprecedented demands for change. The traditional education mode, which focuses on the inculcation and memory of knowledge, has been difficult to meet the needs of cultivating talents needed by the future society. In today's world, there is more emphasis on innovative thinking, practical ability, and lifelong learning ability, which requires that the education system must shift to a teaching model that emphasizes more active student participation, experiential learning, and problem-solving. Outdoor education, as a unique form of education, with its openness, practicality, and experience, has become an important way to cultivate these abilities. It allows students to go out of the classroom, experience nature and society, and solve problems through observation, experiment and cooperation, thus enhancing students' social responsibility, teamwork ability, and ability to adapt to environmental changes [1].

However, outdoor education also faces many challenges, such as uneven resource allocation, difficulty in quantifying learning effects, and safety risk management. Therefore, how to use modern information technology, especially artificial intelligence (AI) and augmented reality (AR) technology [2], to overcome these challenges and improve the efficiency and effectiveness of outdoor education has become an important issue in current educational technology research. The integration of AI and AR technology has brought unprecedented opportunities to the field of education. AI can provide personalized learning recommendations, intelligent evaluation, and instant feedback, while AR creates a highly immersive, interactive learning environment through the seamless integration of virtual and real worlds, making the learning process more attractive and engaging. This technology fusion can not only enrich educational resources, realize dynamic adjustment and real-time update of learning content, but also customize personalized learning paths according to the characteristics and needs of each learner, thus significantly improving the quality of teaching and promoting students to comprehensively and deeply master knowledge and skills [3]. The application of AI and AR technology will also help narrow the gap between urban and rural educational resources, provide high-quality outdoor learning experiences for students in remote areas, and promote educational equity. At the same time, it can also help teachers better monitor students' learning progress [4], adjust teaching strategies in time, and improve teaching efficiency.

The core of this study aims to explore the harmonious coexistence of outdoor education and advanced technology, focusing on how to skillfully integrate artificial intelligence (AI) and augmented reality (AR) technology on the basis of maintaining the essential characteristics of outdoor education [5], creating an immersive learning ecosystem that not only ensures students' safety but also greatly improves learning efficiency. The study is deeply concerned with establishing the basic principles for designing such learning environments, emphasizing that technology application needs to closely match the teaching purpose with the individual characteristics of learners in order to achieve optimal learning outcomes. Specifically, our research agenda includes four key objectives: first, to reveal the key elements and potential limitations of successful implementation of AI and AR technologies in outdoor education scenarios through detailed analysis of existing cases, and to provide an empirical basis for subsequent design; second, we will design a comprehensive model framework that not only clarifies the details of technical architecture, but also covers innovative design principles for content creation processes and teaching activities, aiming to ensure seamless integration of technology and educational content; Furthermore, the research will advance to the development and testing stage of prototype system, and scientifically measure its actual effect on students' academic performance improvement [6], learning motivation stimulation and practical skills enhancement through rigorous evaluation system.

This study is organized as follows to progressively clarify the technical design, implementation, and validation of the proposed AI–AR immersive learning environment for outdoor education: Section II reviews related studies on artificial intelligence, augmented reality, outdoor education, and immersive learning theory to establish the research context. Section III analyzes system requirements and design principles. Section IV presents the system framework and details the implementation of core functional modules, including navigation and positioning, virtual tours, and scenario simulation. Section V reports practical deployment cases and quantitative effect evaluation based on controlled experiments. Finally, Section VI summarizes the main findings and discusses future research directions.

II. Literature Review

A. Application of AI and AR in Education

In an educational model that integrates artificial intelligence and augmented reality, the synergy of technology further broadens the boundaries of education and creates unprecedented learning experiences for students. In their study, they predicted the potential impact of intelligent augmented reality systems in education, arguing that such systems can dynamically adjust content according to students' learning style and progress, providing highly personalized learning scenarios [7]. For example, combining AI's adaptive learning platform with AR technology can create a virtual laboratory for each student that matches their cognitive development level, enabling students to safely perform complex experimental operations such as chemical reaction simulation or physical law verification in virtual environments without worrying about material limitations or safety risks.

In addition, in the study of game-based learning, it is proposed that an immersive environment can enhance students' participation and problem-solving ability, which has been fully demonstrated in outdoor education supported by AI and AR technology [8]. Through AI analysis of students' behavior data in outdoor activities, educators can accurately identify students' knowledge blind spots and skill defects in practice, and then use AR technology to superimpose learning content in real environments, such as real-time identification and provision of plant information in botanical investigations, or display the dynamic process of terrain changes during geographical exploration, thus realizing instant feedback and deep reinforcement learning in real-world learning activities.

B. Outdoor Education

Outdoor education emphasizes experiential learning in a natural environment with its unique educational approach. Outdoor education is defined as a process of learning through direct experience of natural and social environments, which not only imparts knowledge but also focuses on skill development, emotional development, and value formation [9]. Outdoor education is particularly beneficial in developing critical thinking, teamwork, and leadership skills that are difficult to fully develop in traditional classroom settings, according to the study. While outdoor education has many benefits [10], it also faces many challenges. In their review, they summarize several key challenges in outdoor education, including safety risk management, uneven resource allocation, and quantitative evaluation of educational effectiveness [11]. Safety concerns are paramount, and the unpredictable nature of outdoor activities requires a high degree of preparation and professional instruction.

Facing these challenges, the integration of modern technology provides new solutions and development opportunities for outdoor education. In terms of safety risk management, GPS tracking systems and smart wearable devices can be used to monitor student locations in real time, prevent hazards, and respond quickly in emergency situations. The application of these technologies has greatly improved the safety of outdoor activities, while reducing the excessive dependence on professionals [12], making more schools and educational institutions confident to carry out outdoor education programs. With regard to the uneven distribution of resources, the spread of digital platforms and online educational resources has provided access to high-quality outdoor educational resources in remote areas and resource-poor schools. For example, through virtual reality (VR) technology, students can "immersively" explore natural scenery and experience history and culture even in places where field conditions are not available. The introduction of this technology, although not a complete substitute for the real outdoor experience, can alleviate the geographical differences in resource allocation to a certain extent [13].

C. Immersion Learning Theory

Immersion learning theory is derived from cognitive psychology and constructivist learning theory, emphasizing the promotion of deep learning through highly participatory environments. Immersion learning is defined in his research as a way of learning in which learners are fully engaged by simulating real situations [14], which can stimulate learners' desire for exploration and creative thinking. "Situational Cognition" theory further points out that learning takes place in a specific sociocultural context, emphasizing the importance of situation for knowledge construction. Immersion learning theory is increasingly used in education [15], especially after combining AI and AR technologies. The study shows how AR technology can be used to create immersive learning environments for history lessons, where students visit virtual historical scenes through AR glasses, and this interactive and intuitive way of learning significantly improves learning interest and memory of historical events [16]. At the same time, the research uses an AI-driven virtual laboratory to realize immersive learning in biology teaching, and students complete experiments through virtual operation, which not only reduces the experimental cost and safety risk [17], but also improves the learning effect. Immersion learning theory has also shown remarkable results in language learning. The research shows that the intelligent language learning environment constructed by AI technology can provide personalized learning content and real-time dialogue practice according to learners' language level and learning preference [18]. This highly interactive learning mode greatly improves language acquisition efficiency and oral expression ability. AI makes the learning process more efficient and accurate by analyzing learners' grammatical errors, pronunciation problems, etc. in simulated conversations and giving immediate feedback and correction suggestions. AR technology also plays an important role in art and design education. The application of AR in visual arts curriculum is studied. Students can create freely in virtual space and experience different artistic media and techniques through AR equipment [19]. This intuitive operation mode not only inspires students' creativity, but also promotes the understanding of artistic principles and history. AR technology enables students to "walk inside" paintings, observe and analyze works from different angles, providing new perspectives for art appreciation and criticism. The successful construction of an immersive learning environment also needs to consider learners' psychological acceptance and adaptability. In their review, they caution that despite the many advantages of immersive technology [20], excessive reliance on technology can lead to cognitive overload and affect learning outcomes. Educators should therefore balance the use of technology with traditional teaching methods when designing immersion learning activities to ensure that the integration of technology enhances the learning experience while maintaining the effectiveness of learning.

III. Demand Analysis

A. Design Principles

The design of outdoor education immersive learning environment should adhere to the core principles to optimize learning effectiveness, ensure experience and safety, and the specific design principles are shown in Fig. 1. The first principle is contextual relevance, which means that learning scenarios need to be closely integrated with the real world, such as using AR technology to simulate ecosystem operations in ecology courses. Through the combination of GPS and AR, learners can obtain real-time information during field visits and improve their understanding. Secondly, the learner-centered principle emphasizes customizing personalized paths according to individual needs, interests, and styles, analyzing learning data with AI algorithms, dynamically adjusting the difficulty and form of content, and ensuring that each learner grows up in a challenge that suits them. In terms of security, the design needs to ensure physical and information security, adopt encryption technology, establish virtual boundaries, provide security guidelines, and build a worry-free learning environment. The principles of interaction and collaboration advocate enhanced social skills and teamwork through AI-driven role-playing and team challenges, such as AR virtual treasure hunting.

B. Demand Analysis

In the immersive learning environment of outdoor education, the deep integration of technology and education requires careful consideration of the specific needs of various stakeholders to ensure the accurate application and maximum benefit of AI and AR technologies.

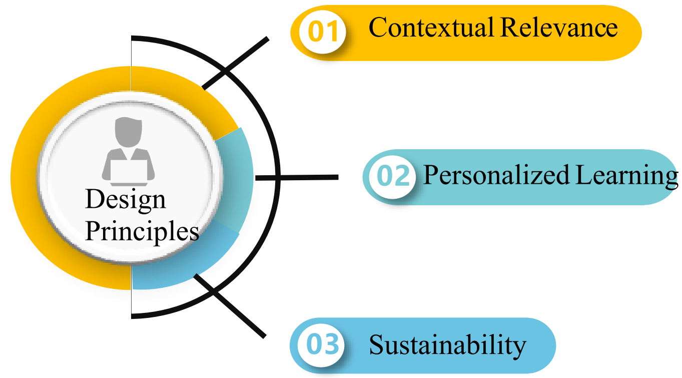


Fig. 1. Design principles.

For learners, the key lies in satisfying their quest for personalized learning experiences. Students expect customized content based on their interests, learning speed and abilities. AI technology is precisely able to provide this customized service by intelligently analyzing learning data, planning the most suitable learning path for each student, and giving timely feedback, thus enhancing the pertinence and effectiveness of learning. At the same time, using AR technology, students can participate in operations that are difficult to achieve in real environments, such as simulating complex natural phenomena or operations [21], which not only increases the fun of learning but also deepens the understanding of knowledge.

Teachers, on the other hand, are eager to have convenient teaching aids to simplify the planning and management of immersive learning activities. This means an intuitive and easy-to-use platform that helps teachers quickly create engaging AR learning content while monitoring and evaluating student learning performance in real-time. In addition, the professional development of teachers should not be ignored. They need to receive training on the application of AI and AR technologies in education and learn how to flexibly use these advanced technologies in outdoor environments to promote teaching innovation and efficiency.

Education managers play the role of resource allocation and strategic planning in technology integration. They need to ensure that all technical facilities, including hardware, software, and network services, are properly configured and maintained, while taking into account cost-effectiveness and maximizing the use of resources. In addition, it is essential to have an efficient data management system that not only helps administrators evaluate learning outcomes through data analysis and provides data support for future educational decisions [22], but also ensures that students' personal information is strictly protected during data processing.

IV. Design Framework for Immersive Learning Environment in Outdoor Education Space

A. Technical Architecture

Hardware devices constitute the physical interface of an immersive learning environment, and their selection and deployment are directly related to the perceived quality and interaction efficiency of learners in outdoor scenes. Key devices include, but are not limited to, augmented reality (AR) headsets, smart Mobile device, global positioning system (GPS) receivers, and environmental monitoring sensors. AR headset, as the core technical equipment, creates a unique mixed reality visual experience for learners by seamlessly integrating virtual information with the real world, deepening cognitive understanding and situational awareness. As a terminal for information processing and feedback, an intelligent Mobile device supports instant content reception, operation feedback, and interactive control, and its portability and flexibility significantly improve the convenience of outdoor learning. The application of GPS positioning and environmental sensors ensures accurate positioning and safety monitoring of learning activities in complex outdoor environments [23], adding an important technical guarantee for the safe implementation of practical activities.

B. Function Module Design

In the design of an immersive learning environment in an outdoor education space, the careful construction of functional modules is the key to realize efficient learning experience. This section discusses in detail the four core modules of navigation and positioning, virtual navigation, situational simulation, and real-time feedback systems, and how they are combined with artificial intelligence algorithms. The specific functional modules are shown in Fig. 2.

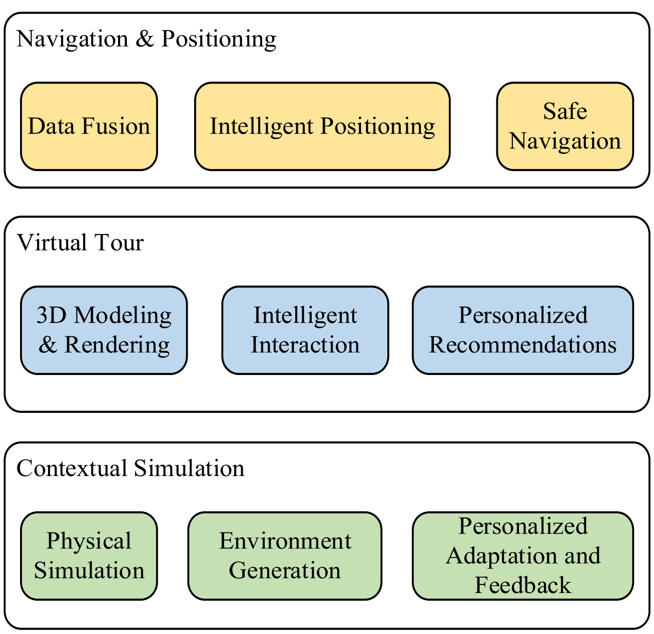


Fig. 2. Functional module design.

1) Navigation and positioning: In the proposed immersive outdoor learning system, navigation and positioning are implemented as a real-time service module directly supporting learner guidance, safety monitoring, and context-aware AR content triggering, rather than as an abstract demonstration of classical filters [24]. The core task of this module is to continuously estimate learner position states and to determine safe and adaptive movement paths under outdoor uncertainty.

A hybrid state estimation framework is adopted, in which particle filtering is not used as a generic replacement for Kalman filtering but is selectively activated when GPS signal quality falls below a predefined threshold. The learner state is defined as:

$$\mathbf{x}_t = [x_t, y_t, v_t, \theta_t] \tag{1}$$

representing planar position, velocity, and heading. Particle weights are updated according to observation confidence derived from sensor reliability indicators [25]:

$$w_t^{(i)} = \frac{w_{t-1}^{(i)}\, p(\mathbf{z}_t \mid \mathbf{x}_t^{(i)})}{\sum_{k=1}^{N} w_{t-1}^{(k)}\, p(\mathbf{z}_t \mid \mathbf{x}_t^{(k)})} \tag{2}$$

where, $p(\mathbf{z}_t \mid \mathbf{x}_t^{(i)})$ is dynamically scaled by GPS signal-to-noise ratio and inertial drift error. This adaptive weighting mechanism enables robust localization during forested or terrain-shielded activities, directly supporting stable AR overlay alignment [26].

To reduce cumulative drift and improve long-term consistency, multi-sensor fusion is executed at fixed temporal windows using a weighted least squares solver:

$$\hat{x} = (H^T W H)^{-1} H^T W z \tag{3}$$

where, weights in $\mathbf{W}$ are updated online based on recent residual errors, allowing the system to downweight unreliable sensors without manual recalibration.

For safety assurance, obstacle avoidance is integrated into the positioning loop rather than treated as an independent process. A lightweight random forest classifier predicts obstacle presence from depth and motion features, and its output constrains the heuristic function of the A* planner:

$$f(n) = g(n) + \lambda h(n) \tag{4}$$

where, λ is adaptively increased in high-risk zones to prioritize safer routes over shorter paths. This coupling ensures that navigation decisions are both context-aware and system-executable, enabling reproducible and verifiable learner movement control during outdoor learning tasks.

2) Virtual tours: The virtual tour module is implemented as an executable interaction layer that directly links spatial perception, semantic content delivery, and learner-driven navigation decisions, rather than serving as a conceptual illustration of AR technologies [27]. Its primary function is to support context-aware knowledge triggering and adaptive route guidance during outdoor learning tasks.

Environmental reconstruction is performed using stereo vision only at predefined anchor points instead of continuous global modeling, reducing computational load on mobile AR devices. For each anchor region, the scene geometry is represented by a sparse landmark set $\mathrm{P} = \{p_i\}$, and the epipolar constraint is applied to validate landmark consistency [28]:

$$p_i'^T \mathbf{F} p_i = 0 \tag{5}$$

where, $\mathbf{F}$ is estimated online from matched feature pairs and is used exclusively to align virtual annotations with real-world surfaces. This formulation ensures that AR overlays remain stable during learner movement rather than optimizing photorealistic reconstruction.

Visual realism is selectively enhanced only for instructional objects that require depth or structural perception. Instead of full-scale ray tracing, a bounded illumination model is applied [29]:

$$L_o = L_e + \alpha \sum_{k=1}^{K} L_i^{(k)} \cos\theta_k \tag{6}$$

where, α controls rendering cost and is adjusted according to device performance constraints, enabling reproducible deployment across heterogeneous hardware.

Natural language interaction is constrained to a task-oriented command set to ensure system reliability. Speech input is processed using a lightweight sequence model:

$$P(y_t \mid y_{<t}, c) = \mathrm{Softmax}(Wh_t) \tag{7}$$

where, the context vector c is derived from the current learning node rather than open-domain dialogue, directly mapping commands to navigation or content queries.

Personalization is achieved through short-horizon behavior modeling instead of generic interest prediction. Learner movement and interaction sequences are encoded as:

$$h_t = f(h_{t-1}, x_t), \quad r_t = g(h_t) \tag{8}$$

where, r ranks nearby learning nodes and updates tour paths in real time. This tightly coupled design establishes a verifiable link between algorithm execution, system behavior, and adaptive learning outcomes in outdoor virtual tours.

3) Scenario simulation: The scenario simulation module is implemented as a task-driven execution engine that supports experiential learning objectives by dynamically generating, controlling, and evaluating simulated events aligned with outdoor educational tasks. Rather than presenting generic physical or generative models, this module focuses on how simulation states are computed, adapted, and validated within the operational system.

Each scenario is formalized as a controllable state space:

$$\mathrm{S}_t = \{\mathbf{x}_t, \mathbf{e}_t, d_t\} \tag{9}$$

where, $\mathbf{x}_t$ denotes the physical state of simulated entities, $\mathbf{e}_t$ represents environmental parameters (terrain, weather, visibility), and d_t encodes difficulty level. Physical interaction is resolved using a constrained dynamics solver derived from the Newton–Euler formulation:

$$\mathbf{M}\ddot{\mathbf{x}}_t = \sum \mathbf{F}_t - \beta \dot{\mathbf{x}}_t \tag{10}$$

where, β is an adaptive damping coefficient adjusted to learner motor performance, enabling reproducible accessibility control for different learner groups.

Scenario content generation is not performed through unconstrained GAN or VAE sampling. Instead, generative models are conditioned on pedagogical labels c and spatial context l [30]:

$$\min_G \max_D \mathbb{E}_{x\sim p(x|c,l)}[\log D(x)] + \mathbb{E}_z[\log(1 - D(G(z \mid c,l)))] \tag{11}$$

ensuring that generated scenes correspond to predefined learning objectives and locations. Generated scenarios are cached and reused under identical conditions to guarantee experimental reproducibility.

Adaptive progression is governed by a reinforcement learning policy embedded in the simulation controller. The learner–scenario interaction is modeled as a Markov decision process, and task difficulty is updated according to:

$$Q(s,a) \leftarrow Q(s,a) + \alpha\left[r_t - \lambda d_t + \gamma \max_{a'} Q(s',a') - Q(s,a)\right] \tag{12}$$

where, r_t reflects task completion quality and λd_t penalizes excessive cognitive load. This closed-loop design explicitly links algorithm execution to scenario evolution, learning outcomes, and system-level validation across repeated trials.

V. Practical Cases and Effect Evaluation

A. Implementation Cases

The implementation was conducted as a controlled field experiment to ensure methodological rigor and verifiability. The study site was a designated nature reserve, and participants were drawn from the same grade level and educational background to reduce confounding effects. A total of two groups were formed: an experimental group using the proposed AI–AR immersive learning system and a control group receiving conventional outdoor instruction. Both groups followed identical learning objectives, curricular content, activity duration, and instructor guidance, with the only controlled variable being the use of the immersive system.

The experimental system was deployed using a standardized hardware and software configuration, including AR head-mounted displays, mobile devices with integrated

GPS, and a cloud-based platform providing content management, user logging, and real-time feedback services. All learning activities were predefined and time-synchronized across participants to ensure consistency. Interaction data (navigation paths, task completion time, and system prompts), assessment scores, and questionnaire responses were collected as structured datasets.

The experimental procedure consisted of four phases: pre-test assessment, guided learning intervention, post-test assessment, and feedback collection. Learning performance was evaluated using identical pre- and post-tests, while engagement and perception were measured using validated Likert-scale instruments. Data analysis focused on between-group comparisons under the same experimental conditions, allowing observed performance differences to be attributed to the system intervention. Experimental constraints, including limited sample size and site specificity, are acknowledged to delimit the generalizability of the results.

B. Effect Evaluation

To improve methodological rigor and result verifiability, the effect evaluation was conducted under controlled experimental conditions with consistent instructional content, duration, and assessment instruments for both groups. All reported indicators were derived from paired pre-test and post-test measurements. Descriptive statistics and inferential analysis were applied to examine between-group differences.

Learning interest and participation were measured using a standardized questionnaire administered before and after the intervention. Mean percentage increases were calculated for each group, and independent-sample t-tests were performed to examine statistical significance at the 0.05 level.

TABLE I. COMPARISON OF INTEREST AND PARTICIPATION IN LEARNING

Group	Increase in Interest in Learning (%)	Increase in Participation (%)
Experimental Group	60	75
Control Group	20	15

TABLE II. ASSESSMENT OF KNOWLEDGE MASTERY

Test Content	Experimental Group Mean Score	Control Group Mean Score	Fractional Difference
Biodiversity Knowledge	85	70	15
Ecosystem Understanding	90	75	15

The results in Table I indicate that the experimental group exhibited significantly greater gains in both learning interest and participation ($p < 0.05$), suggesting that the immersive system had a measurable motivational effect beyond traditional outdoor instruction.

Knowledge mastery was evaluated using identical post-intervention tests covering biodiversity knowledge and ecosystem understanding. Mean scores and between-group differences are reported in Table II.

Independent-sample t-tests confirmed that both score differences were statistically significant ($p < 0.05$). These results indicate a consistent learning advantage associated with the immersive learning environment.

Problem-solving ability was assessed through task-based performance rubrics evaluated by two independent raters. Improvement ratios were computed based on normalized pre–post score differences.

TABLE III. IMPROVEMENT OF PROBLEM-SOLVING ABILITY

Evaluation Index	Experimental Group Promotion Ratio (%)	Control Group Promotion Proportion (%)
Observation and Analysis Ability	45	20
Innovative Thinking and Decision Making	50	15

As shown in Table III, the experimental group demonstrated substantially higher improvement across both cognitive dimensions. While the results consistently favor the proposed system, the evaluation is limited by sample size and single-site deployment, which may constrain generalizability. Future studies will incorporate larger datasets and multi-site trials to further validate these findings.

C. User Feedback

Table IV shows the results of the student satisfaction survey. In terms of interactive experiences, 70% of students expressed great satisfaction, and 20% expressed satisfaction. In terms of content richness, 65% of students expressed great satisfaction and 25% expressed satisfaction. In terms of technical stability, 85% of students expressed great satisfaction and 10% expressed satisfaction. In terms of security, 90% of students expressed great satisfaction and 8% expressed satisfaction. These data show that most students are satisfied with the teaching methods and activity design of the experimental group.

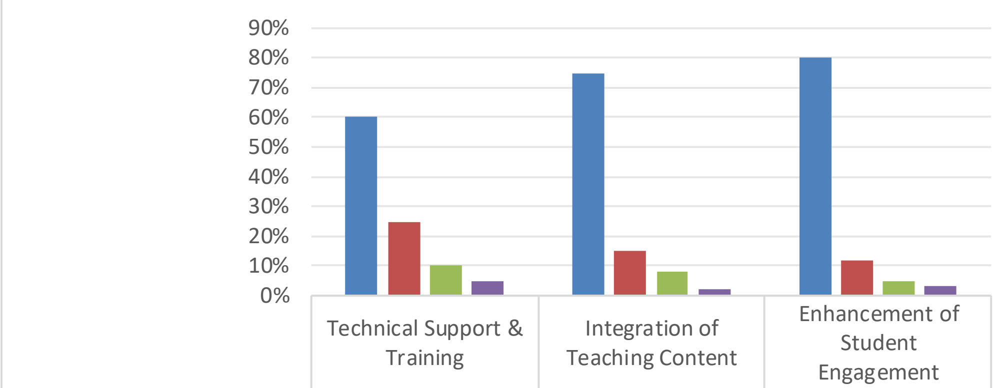
TABLE IV. STUDENT SATISFACTION SURVEY

Feedback Field	Very Satisfied (%)	Satisfaction (%)	General (%)	Not Satisfied (%)
Interactive Experience	70	20	8	2
Content Richness	65	25	8	2
Technical Stability	85	10	3	2
Sense of Security	90	8	2	0

Fig. 3 presents the results of the evaluation of teachers' teaching experience. In terms of technical support and training, 60% of teachers thought it was very useful, and 25% thought it was useful.

D. Results and Discussion

The experimental results demonstrate that the proposed AI–AR immersive learning environment produces consistent and measurable improvements across cognitive, behavioral, and affective dimensions of outdoor learning. Quantitative comparisons between the experimental and control groups indicate significant gains in learning interest, participation, knowledge mastery, and problem-solving ability under controlled instructional conditions. These results suggest that the integration of adaptive navigation, context-aware virtual tours, and task-driven scenario simulation effectively enhances learner engagement and learning efficiency beyond traditional outdoor education approaches.



	Technical Support & Training	Integration of Teaching Content	Enhancement of Student Engagement
Highly Useful	60%	75%	80%
Useful	25%	15%	12%
Average	10%	8%	5%
Room for Improvement	5%	2%	3%

Fig. 3. Evaluation of teachers' teaching experience.

From a system perspective, the results validate the practical effectiveness of the algorithm–module coupling proposed in the technical framework. Improvements in learning outcomes can be directly associated with system mechanisms such as real-time spatial alignment, adaptive difficulty adjustment, and feedback-driven task progression. This linkage confirms that the observed performance gains are not incidental but emerge from executable system behavior.

However, the results should be interpreted within defined constraints. The current evaluation is limited to a single-site deployment and a finite sample size, which may restrict generalizability across different educational contexts and age groups. Additionally, environmental variability and device heterogeneity may influence system performance. Future work will extend multi-site trials, incorporate larger datasets, and refine statistical modeling to further strengthen external validity and comparative analysis.

VI. Conclusion

In the context of ongoing educational transformation, this study advances outdoor education research by developing and validating an AI–AR–enabled immersive learning environment with explicit system-level implementation and evaluation. Beyond practical application, the study contributes a structured design paradigm that links adaptive navigation, virtual tours, and scenario simulation to executable algorithms and measurable learning outcomes, extending existing immersive learning frameworks from conceptual models to deployable systems. Empirical results from controlled experiments confirm that the proposed environment effectively enhances learner engagement, knowledge acquisition, and problem-solving ability, demonstrating its technical and educational validity.

Despite these contributions, several limitations remain. The current evaluation is based on a single-site deployment with a limited sample size, which may constrain the generalizability of the findings across diverse educational contexts and learner populations. Environmental variability and device heterogeneity may also affect system performance. Future research will focus on multi-site longitudinal studies, larger and more diverse datasets, and refined statistical modeling to further validate robustness, scalability, and cross-context applicability of the proposed system.

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