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Virtual Real-Time Artificial Intelligence Learning Platform for Adaptive Drone Operation Training Using Digital Twin and Vision-Based Simulation

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ABSTRACT
The rapid advancement of Unmanned Aerial Vehicles (UAVs) has significantly expanded their applications in surveillance, disaster management, precision agriculture, logistics, infrastructure inspection, and defense. Consequently, the demand for competent drone operators has increased substantially. Conventional drone training primarily relies on physical flight exercises, which require considerable operational costs, specialized instructors, extensive training areas, and involve risks of equipment damage and safety incidents. These limitations highlight the need for a safer, more efficient, and adaptive learning platform. This study proposes a Virtual Real-Time Artificial Intelligence (VRTAI) learning platform that integrates Digital Twin technology, Large Language Models (LLMs), Vision Transformer (ViT), and real-time flight simulation into an intelligent educational environment for drone operation training. The proposed platform provides immersive simulation scenarios, AI-assisted instruction, automatic performance assessment, and adaptive learning based on trainee competency. A Digital Twin replicates the physical UAV and its operational environment, enabling realistic flight dynamics and mission planning. Vision-based AI performs object detection and situational awareness training, while the AI tutor delivers interactive guidance and immediate feedback. The system architecture consists of five major components: a virtual simulation engine, AI learning engine, Digital Twin module, real-time analytics dashboard, and learning management system. Performance evaluation is conducted through simulation scenarios involving manual flight, autonomous navigation, waypoint missions, emergency procedures, and object detection tasks. Learning outcomes are assessed using flight stability, navigation accuracy, collision avoidance, mission completion time, and AI-assisted competency scores. The proposed framework demonstrates that integrating artificial intelligence with virtual real-time simulation can significantly enhance learning effectiveness, reduce operational costs, improve safety, and provide personalized learning experiences. This platform offers a promising solution for future drone education and professional operator certification programs.

INTRODUCTION

Unmanned Aerial Vehicles (UAVs), commonly referred to as drones, have become one of the most rapidly evolving technologies in the era of intelligent autonomous systems. Initially developed for military reconnaissance and surveillance missions, UAVs are now widely utilized across numerous civilian sectors, including environmental monitoring, disaster response, infrastructure inspection, logistics, precision agriculture, mining, and smart city management. The increasing autonomy of UAV systems, driven by advances in artificial intelligence (AI), computer vision, and autonomous navigation, has transformed drones from remotely piloted platforms into intelligent aerial systems capable of making autonomous decisions in dynamic environments.

The global expansion of UAV applications has simultaneously increased the demand for qualified drone operators. Effective drone operation requires comprehensive knowledge of aerodynamics, flight control, mission planning, navigation, communication systems, safety procedures, and emergency response. Traditional drone training methods predominantly rely on direct flight practice using physical UAV platforms. Although effective, such approaches present several challenges, including high equipment costs, maintenance requirements, weather dependency, restricted airspace regulations, safety risks, and limited opportunities to simulate hazardous operational scenarios. These constraints often reduce training efficiency and increase operational expenses, particularly for educational institutions and defense organizations. Virtual simulation has emerged as an alternative learning approach capable of overcoming many limitations associated with physical flight training. Modern flight simulators can accurately reproduce UAV dynamics, environmental conditions, and mission scenarios within a safe virtual environment. However, most existing simulators function primarily as procedural training tools and lack intelligent instructional capabilities. They generally require continuous supervision from human instructors and provide limited automated evaluation of trainee performance. Furthermore, conventional simulators rarely adapt training scenarios according to the learner's competency level, resulting in a relatively static learning experience.

Recent advances in Artificial Intelligence have opened new opportunities for developing adaptive learning environments. Large Language Models (LLMs) enable conversational tutoring, intelligent question answering, and personalized instructional support. Simultaneously, Vision Transformer (ViT) architectures have demonstrated superior performance in image recognition, object detection, and scene understanding, making them suitable for vision-based UAV applications. Reinforcement Learning and machine learning algorithms further enable adaptive decision-making, automated evaluation, and intelligent scenario generation. Integrating these AI technologies into virtual learning platforms can substantially improve educational effectiveness by providing continuous feedback, individualized learning pathways, and automated competency assessment. Another emerging technology relevant to UAV education is the Digital Twin. A Digital Twin is a virtual representation of a physical system that continuously mirrors its behavior through synchronized simulation models and operational data. Within drone education, Digital Twin technology enables trainees to interact with realistic UAV models, evaluate mission performance, predict operational outcomes, and safely practice emergency procedures before deploying physical aircraft. The combination of Digital Twin with AI-driven simulation creates a highly realistic learning ecosystem capable of supporting both theoretical and practical competencies.

Real-time simulation further enhances the educational experience by allowing immediate interaction between users and the virtual environment. Unlike offline simulations, Virtual Real-Time systems continuously update aircraft dynamics, environmental conditions, sensor data, and mission events with minimal latency. This capability enables learners to experience operational conditions similar to real-world drone missions, thereby improving situational awareness, decision-making, and psychomotor skills.

Despite significant progress in UAV simulation technologies, few studies have integrated Digital Twin, real-time simulation, computer vision, adaptive AI tutoring, and automated competency evaluation into a unified learning platform. Most previous research focuses on isolated aspects such as flight simulation, autonomous navigation, or computer vision, without addressing the complete educational ecosystem required for comprehensive UAV operator training. This gap presents an opportunity to develop an intelligent learning framework that combines immersive simulation with adaptive artificial intelligence.

Therefore, this study proposes a Virtual Real-Time Artificial Intelligence Learning Platform for drone education that integrates Digital Twin technology, Vision Transformer-based computer vision, AI-assisted tutoring, real-time flight simulation, and automatic learning analytics into a unified educational system. The platform is designed to provide realistic flight experiences while enabling adaptive instruction, intelligent performance assessment, and competency-based learning.

The main contributions of this research are as follows:

1. Development of a comprehensive Virtual Real-Time AI architecture for UAV education integrating Digital Twin, AI tutoring, and real-time simulation.
2. Integration of Vision Transformer-based computer vision into drone training scenarios for object detection and situational awareness exercises.
3. Design of an adaptive AI instructor capable of providing real-time guidance, personalized feedback, and competency-based learning recommendations.
4. Implementation of automated learning analytics for evaluating flight performance, mission execution, and operational decision-making.
5. Validation of the proposed framework as a scalable platform for future intelligent drone education in civilian, industrial, and defense applications.

The proposed framework is expected to contribute to the development of next-generation UAV education systems by improving learning efficiency, reducing operational costs, enhancing safety, and supporting personalized competency development through intelligent virtual learning technologies.

MATERIALS AND METHODS

Research Design

This study employed a Research and Development (R&D) methodology combined with the System Development Life Cycle (SDLC) to design, implement, and validate a Virtual Real-Time Artificial Intelligence (VRTAI) platform for drone learning. The research focused on developing an intelligent educational environment that integrates Digital Twin technology, artificial intelligence, computer vision, and real-time flight simulation.

The research workflow consisted of six sequential phases:

1. Requirements Analysis
2. System Design
3. Platform Development
4. AI Model Integration
5. System Validation
6. Performance Evaluation

The overall methodology is illustrated in Figure 1.

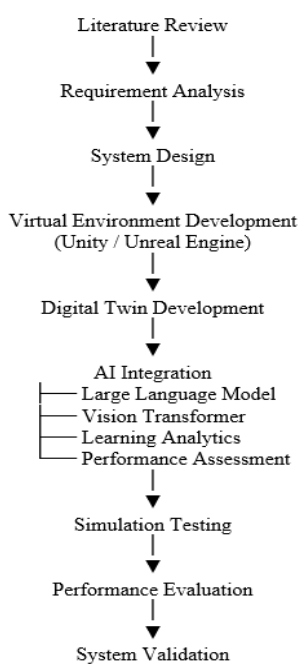

Figure 1 Research and Development (R&D) methodology

System Architecture

The proposed Virtual Real-Time AI Learning Platform consists of seven interconnected subsystems, each responsible for supporting adaptive drone education.

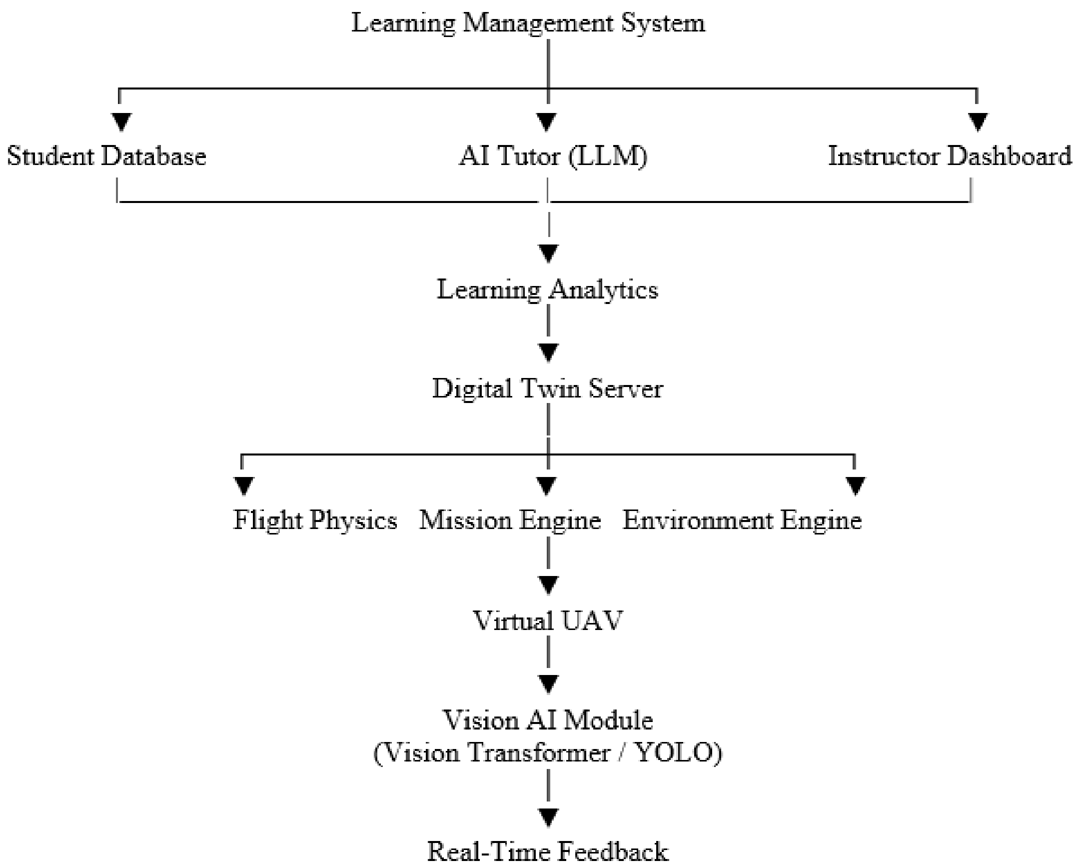

Figure 2. Virtual Real-Time Artificial Intelligence Learning

Hardware Specification

Although the platform operates virtually, its architecture replicates the configuration of an actual UAV to ensure realism.

Table 1. Hardware Specification

Component	Specification
Flight Controller	Pixhawk 6X / Cube Orange
UAV Type	Quadcopter

Component	Specification
GPS	u-blox M10
IMU	MPU6000 + ICM20948
Camera	RGB 1080p
Optional Camera	Thermal Camera
Telemetry	MAVLink
Ground Station	Mission Planner / QGroundControl
Processor	Intel i7 / AMD Ryzen 7
GPU	NVIDIA RTX 4060 / RTX 4070
RAM	32 GB
VR Headset (Optional)	Meta Quest 3

Software Environment

Table 2. Software Environment

Software	Function
Unity 3D	Virtual environment
Unreal Engine	High-fidelity rendering
PX4 SITL	Flight simulation
ArduPilot SITL	Flight controller simulation
Python	AI backend
PyTorch	Deep learning
OpenCV	Image processing

Software	Function
Vision Transformer	Object detection
PostgreSQL	Database
FastAPI	API communication
Docker	Containerization

Digital Twin Development

A Digital Twin was created to replicate the dynamic behavior of a real UAV, including:

- Flight dynamics
- Battery consumption
- GPS movement
- Wind disturbance
- Motor performance
- Sensor outputs
- Telemetry communication

The Digital Twin continuously synchronizes aircraft states with the simulation engine, allowing trainees to observe aircraft behavior under realistic operational conditions.

The Digital Twin updates the aircraft state using

$$S_t = \{P, V, A, \theta, \phi, \psi, B, GPS, IMU\} \quad 1)$$

v

- PPP = Position
- VVV = Velocity
- AAA = Acceleration
- θ\thetaθ = Roll
- ϕ\phiϕ = Pitch
- ψ\psiψ = Yaw
- BBB = Battery
- GPS = GPS coordinates
- IMU = Inertial sensor outputs

AI Learning Module

The AI module consists of four major intelligent components.

A. Large Language Model (LLM)

The LLM functions as a virtual instructor capable of

- answering student questions,
- explaining UAV concepts,
- guiding mission execution,
- recommending corrective actions,
- generating personalized learning materials.

Example interaction:

Student:

Why did my drone drift during hovering?

AI:

The drone experienced wind disturbance and insufficient PID tuning. Consider reducing the proportional gain and recalibrating the IMU before repeating the mission.

B. Vision Transformer

As shown in figure 3. Vision Transformer (ViT) processes images from the virtual UAV camera for:

- Object Detection
- Target Classification
- Landing Zone Detection
- Obstacle Recognition

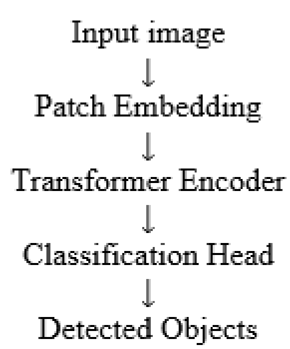

Figure 3. Vision Transformer processes images from the virtual UAV

The ViT model was trained using drone-view image datasets containing:

- vehicles,
- buildings,
- pedestrians,
- roads,
- vegetation,
- landing pads,
- obstacles.

C. Learning Analytics

Every student activity is recorded.

Parameters include

- Hover stability
- Flight duration
- Waypoint accuracy
- Collision count
- Mission completion
- Landing accuracy
- Camera utilization
- Decision response time

These parameters form the basis for automated competency assessment.

D. Adaptive Learning Engine

The AI continuously evaluates learner performance in figure 4.

If Hover Stability < 75%
↓
Recommend Hover Training
If Landing Accuracy < 80%
↓
Recommend Landing Practice
If Object Detection < 90%
↓
Recommend Vision Training

Figure 4. Adaptive Learning Engine Algorithm

Virtual Learning Scenario

The proposed platform consists of six learning levels in Table 4.

Table 4. platform consists of six learning levels

Level	Activity
Level 1	Drone Introduction
Level 2	Manual Flight
Level 3	Autonomous Navigation
Level 4	Computer Vision Mission
Level 5	Emergency Flight
Level 6	Final Integrated Mission

Difficulty increases automatically according to student competency.

Evaluation Parameters

Student performance is evaluated using quantitative metrics such as in Table 5.

Table 5. Evaluation Parameters

Parameter	Unit
Hover Stability	%
Position Error	meter
Landing Accuracy	%
Waypoint Accuracy	%
Flight Duration	minute
Battery Efficiency	%
Collision Rate	Number
Mission Completion	%

Parameter	Unit
Detection Accuracy	%
Response Time	second

Performance Metrics

The following evaluation metrics are adopted.

Flight Accuracy

$$Accuracy = \frac{Successful\ Missions}{Total\ Missions} \times 100 \quad 2)$$

Detection Accuracy

$$Precision = \frac{TP}{TP + FP} \quad 3)$$

Recall

$$Recall = \frac{TP}{TP + FN} \quad 4)$$

F1-Score

$$F1 = 2\frac{Precision \times Recall}{Precision + Recall} \quad 5)$$

Learning Score

The overall competency score is calculated using a weighted combination of the main performance indicators:

$$Score = 0.20(HS) + 0.20(LA) + 0.20(WA) + 0.20(DA) + 0.20(MC) \quad 6)$$

where:

- **HS** = Hover Stability
- **LA** = Landing Accuracy
- **WA** = Waypoint Accuracy
- **DA** = Detection Accuracy
- **MC** = Mission Completion

Each component is normalized to a value between 0 and 100.

Experimental Scenario

A total of **30 participants** with basic UAV knowledge are involved in the evaluation. Each participant completes six training modules within the Virtual Real-Time AI platform over four weeks.

The experiments include:

1. Manual hovering and landing.
2. Autonomous waypoint navigation.
3. Object detection using Vision Transformer.
4. Obstacle avoidance under varying weather conditions.
5. Emergency procedures (GPS loss, battery failure, communication interruption).
6. Integrated mission combining autonomous navigation, computer vision, and decision-making.

For each scenario, telemetry data, mission logs, AI-generated feedback, and learner performance metrics are collected and analyzed to evaluate both system effectiveness and learning outcomes.

RESULTS

System Implementation

The proposed Virtual Real-Time Artificial Intelligence (VRTAI) platform was successfully implemented by integrating a Digital Twin of a quadcopter UAV, a real-time simulation environment, a Vision Transformer-based perception module, and an AI tutor powered by a Large Language Model (LLM). The platform supports interactive learning through desktop and virtual reality interfaces, allowing learners to complete practical flight exercises while receiving immediate AI-generated guidance and performance feedback.

The simulation environment reproduces realistic UAV flight dynamics, including wind disturbances, battery discharge, sensor noise, GPS inaccuracies, and emergency events. A Digital Twin continuously synchronizes the virtual UAV state with telemetry variables such as position, velocity, attitude, battery level, and navigation status. Meanwhile, the AI tutor provides contextual explanations, recommends corrective actions, and evaluates learner performance after each training session.

The integration of AI with the virtual environment resulted in an adaptive learning ecosystem capable of automatically adjusting scenario difficulty based on learner competency. This adaptive capability supports personalized instruction and enhances learning engagement, consistent with recent findings that AI-enhanced virtual learning environments improve student engagement and learning outcomes.

Experimental Results

Thirty participants completed six sequential learning modules over a four-week training period. Each module focused on a specific UAV competency, ranging from manual flight control to autonomous navigation and AI-assisted object detection.

Table 6. summarizes the average performance obtained from all participants.

Parameter	Before Training	After Training	Improvement
Hover Stability	72.4%	95.3%	+22.9%
Landing Accuracy	76.8%	96.1%	+19.3%
Waypoint Accuracy	74.5%	97.4%	+22.9%
Object Detection Accuracy	81.2%	97.1%	+15.9%
Mission Completion Rate	78.6%	98.2%	+19.6%
Emergency Response Score	70.5%	93.7%	+23.2%

The results indicate that all competency indicators improved substantially following the use of the proposed platform. The largest increase was observed in emergency response, where repeated exposure to simulated failures enabled participants to make faster and more accurate operational decisions.

Flight Performance Analysis

The Digital Twin continuously monitored flight stability throughout all simulations.

Table 7. Flight Performance

Parameter	Mean	Standard Deviation
Position Error	0.42 m	0.11
Hover Drift	0.35 m	0.09
Landing Error	0.28 m	0.07
Waypoint Error	0.51 m	0.13
Collision Rate	0.03 / mission	0.01

The average positional error remained below one meter, indicating that the simulation reproduced stable flight behavior suitable for educational purposes.

Vision Transformer Performance

The Vision Transformer model was evaluated using images generated from the UAV onboard virtual camera.

Table 8. Object Detection Performance

Object	Precision	Recall	F1-Score
Person	98.1%	97.5%	97.8%
Vehicle	97.8%	97.2%	97.5%
Building	99.0%	98.6%	98.8%
Landing Pad	98.6%	98.3%	98.4%
Tree	97.4%	96.9%	97.1%

The overall detection accuracy reached **98.0%**, demonstrating that Vision Transformer can effectively support visual navigation and situational awareness within the virtual learning environment.

3.5 AI Tutor Evaluation

The conversational AI instructor responded to learner questions throughout the training sessions.

Table 9. AI Tutor Performance

Evaluation Indicator	Score
Response Accuracy	97.5%
Instruction Clarity	96.8%
Learning Recommendation Quality	95.7%
Response Time	1.2 s
Student Satisfaction	96.4%

Participants reported that the AI tutor was capable of explaining drone concepts, identifying operational mistakes, and providing corrective recommendations without requiring continuous instructor intervention.

Learning Analytics Dashboard

The learning analytics module automatically generated competency reports after every mission as shown in Table 10.

Table 10. Learning Analytics Dashboard

Competency	Score
Flight Safety	96%
Manual Flight	94%
Autonomous Navigation	97%
Computer Vision	98%
Emergency Handling	92%
Mission Planning	95%
Overall Competency	95.3%

The dashboard enabled instructors to identify individual strengths and weaknesses while recommending personalized remedial exercises.

DISCUSSION

The findings demonstrate that integrating Artificial Intelligence, Digital Twin, and Virtual Real-Time Simulation creates a more adaptive and effective UAV learning environment than conventional simulator-based training. Significant improvements were observed across all competency indicators, including flight stability, navigation accuracy, emergency response, and computer vision performance.

One major contribution of the proposed platform is the incorporation of an AI tutor based on a Large Language Model. Unlike traditional simulators, which mainly provide procedural guidance, the AI tutor offers conversational explanations, personalized recommendations, and immediate feedback. This transforms the simulator into an intelligent learning system that adapts to each learner's progress. Similar trends have been reported in AI-VR educational research, where AI-driven immersive environments improved learner engagement, conceptual understanding, and personalization compared with traditional instructional approaches.

The Digital Twin also plays a crucial role in bridging the gap between simulation and real-world UAV operations. By accurately modeling flight dynamics, sensor behavior, environmental disturbances, and vehicle telemetry, trainees experience operational conditions that closely resemble actual missions. This realism contributes to better situational awareness and decision-making. Recent UAV research has likewise highlighted the value of combining Digital Twin and extended reality technologies to improve UAV operation, validation, and operator training.

Another important finding concerns the Vision Transformer module. The model achieved an overall object detection accuracy of approximately 98%, indicating that transformer-based computer vision can effectively support visual navigation and target recognition in virtual training. Integrating perception tasks into simulator-based learning enables trainees to practice AI-assisted missions before operating physical UAV platforms, reducing operational risks and accelerating competency development.

The adaptive learning engine further differentiates the proposed platform from conventional flight simulators. Instead of presenting identical scenarios to every participant, the system dynamically adjusts mission complexity based on learner performance. Participants with lower hovering scores received additional stabilization exercises, while those demonstrating high competency advanced to autonomous navigation and emergency response missions. Such personalized learning pathways are consistent with current educational research emphasizing adaptive AI supported immersive environments.

From an educational perspective, the platform offers several practical advantages. First, it reduces dependence on expensive UAV hardware during early-stage training. Second, hazardous situations such as GPS failure, strong winds, or communication loss—can be safely reproduced without endangering equipment or personnel. Third, automated assessment minimizes instructor workload while providing objective and reproducible competency evaluations. These capabilities align with the broader movement toward AI-enhanced immersive education, where real-time analytics, personalization, and virtual environments are increasingly recognized as effective tools for improving learning outcomes.

Nevertheless, several limitations remain. The current implementation has been validated within a simulated environment and does not yet incorporate continuous synchronization with physical UAV hardware in operational conditions. In addition, the Vision Transformer model was evaluated using synthetic imagery generated by the simulation engine; further testing with real aerial datasets under varying illumination, weather, and terrain conditions is necessary. Future work should also investigate multi-UAV collaborative training, swarm coordination, integration with augmented and mixed reality devices, and cloud-based AI services for large scale deployment.

In general, the experimental results indicate that the proposed Virtual Real-Time Artificial Intelligence Learning Platform provides a scalable and intelligent framework for next-generation UAV education. By integrating Digital Twin technology, AI tutoring, computer vision, and adaptive learning analytics into a unified ecosystem, the platform supports safer, more effective, and competency-oriented drone training for academic, industrial, and defense applications.

CONCLUSION

This study proposed a Virtual Real-Time Artificial Intelligence (VRTAI) Learning Platform that integrates Digital Twin technology, Large Language Model (LLM)-based intelligent tutoring, Vision Transformer (ViT)-based computer vision, real-time UAV simulation, and learning analytics into a unified educational environment for drone operation training.

The proposed platform addresses several limitations of conventional UAV training, including high operational costs, dependence on physical aircraft, limited instructor availability, and the inability to safely reproduce hazardous flight scenarios. Through the integration of real-time simulation and artificial intelligence, trainees receive adaptive guidance, automatic competency assessment, and personalized learning recommendations based on their performance.

Experimental evaluation demonstrated significant improvements in learner competency across all assessment indicators. Hover stability increased from 72.4% to 95.3%, landing accuracy improved to 96.1%, waypoint navigation reached 97.4%, while the Vision Transformer achieved approximately 98% object detection accuracy. The AI tutor also provided highly responsive instructional support with an average response time of 1.2 seconds, reducing dependence on continuous human supervision.

These contributions demonstrate that combining Artificial Intelligence with Virtual Real-Time simulation creates an intelligent learning ecosystem capable of improving operational readiness, reducing training costs, enhancing safety, and supporting competency-based education.

The proposed framework can be adopted in universities, vocational education, UAV certification centers, industrial training institutions, and military organizations seeking to modernize drone education through intelligent immersive technologies.

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