

Design and Application of a Virtual-Real Fusion Training System for Hilly Agricultural Scenarios: A Case Study on Mountain Drip Irrigation Technology

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Abstract [Objectives] In response to the practical challenges encountered in the hilly agricultural equipment training within agricultural higher vocational colleges, specifically "the inability to access real scenarios, afford actual equipment, and fully practice real processes", a virtual-real fusion training system has been developed, and the effectiveness of this system is demonstrated through its application to mountain drip irrigation technology. [Methods] Utilizing the actual technology project titled "Research and Promotion of Integrated Application of Internet of Things Drip Irrigation Technology in Mountain Planting" as a technical blueprint, a three-tiered progressive training model comprising "virtual simulation, semi-physical joint debugging, and real scene verification" has been developed. It includes four core skill modules: terrain mapping and pipeline network design, LoRa wireless networking, fuzzy PID water and fertilizer decision-making, and cloud-edge collaborative platform operation and maintenance. The framework is also supported by a practical training management platform alongside an assessment and evaluation system. [Results] In the pilot implementation of the system at Huizhou Engineering Vocational College, the per-student training cost has been reduced by approximately 70% compared to the traditional "whole-orchard field attachment" model. Students are able to complete typical training scenarios, such as 30° slope irrigation uniformity control and 1 500-m LoRa communication range, without leaving the campus. Furthermore, their capabilities in managing the entire closed-loop process have been significantly improved. [Conclusions] This system has implemented a practical training teaching reform characterized by "real project-driven, real data training, and real scene transfer", thereby offering a replicable practical pathway for agricultural higher vocational colleges situated in hilly agricultural regions.

Key words Virtual-real fusion, Hilly agriculture, Mountain drip irrigation, Training system, Agricultural higher vocational college, Internet of Things (IoT)

1 Introduction

Mountains and hills account for approximately 43.23% of China's total land area^[1]. The regions surrounding Nankun Mountain and Luofu Mountain in Huizhou City, Guangdong Province, serve as key implementation zones for the "Around Two Mountains" rural revitalization project and represent a core area for the cultivation of high-value-added specialty crops, including macadamia nuts and citrus fruits. Within Boluo County, part of the "Around Two Mountains" area, mountains account for 62.37% of the total land area, while hills comprise 20.53%, resulting in a combined proportion of 82.9%^[2]. This geomorphological characteristic necessitates that local agricultural production relies heavily on highly adaptable and precise irrigation technologies. Furthermore, it imposes specific "hilly and mountainous" requirements on the talent development strategies of agricultural higher vocational colleges in Huizhou^[3].

This article utilizes the project titled "Research and Promotion of Integrated Application of Internet of Things Drip Irrigation Technology in Mountain Planting", conducted by Huizhou Engineering Vocational College (Project No.: 2025SCQ04013; funded with 300 000 yuan from the municipal fiscal special fund; imple-

mentation period: July 2025 to June 2028), as a concrete technical blueprint. The objective is to translate the project's technological research outcomes into practical training and instructional resources, develop and implement a virtual-real fusion practical training system tailored to hilly agricultural environments, and concurrently propose a viable teaching organization plan. This scheme effectively addresses the requirements of hilly agricultural equipment training through a hierarchical and progressive approach, comprising three layers: "virtual simulation for high-risk and high-cost tasks, semi-physical platforms for interface and joint debugging, and real scenes for verification and application transfer"^[4]. Firstly, the virtual layer replicates extreme working conditions at a low cost, such as a steep slope of 30°, signal attenuation, and water hammer effects, thereby overcoming challenges related to "limited access and insufficient practical experience". Secondly, the semi-physical layer integrates real LoRa nodes, pressure compensation drippers, and PLC/single-chip microcomputer controllers into removable physical objects, effectively mitigating issues of "high cost and reluctance to disassemble equipment". Thirdly, the real layer leverages the college's science and technology projects to establish a 1 hm² demonstration base within a cooperative orchard, successfully "bridging the gap between theoretical learning and practical application, and facilitating technology transfer".

This study seeks to develop a talent cultivation system for Internet of Things (IoT) irrigation tailored to the characteristics of

hilly terrains within agricultural higher vocational colleges, addressing the existing gap between general teaching approaches and the specific demands imposed by such terrains. By fostering a deeper integration of industry and education and enhancing students' competencies in applying and maintaining precision agricultural equipment in complex environments, the research aims to improve water use efficiency in the cultivation of high-value crops locally. This contributes to the modernization and transformation of agriculture in the "Around Two Mountains" region. Furthermore, the study offers a replicable practical model for reforming agricultural vocational education in comparable regions, thereby possessing substantial theoretical and practical significance.

2 Problems in practical teaching

Currently, agricultural higher vocational colleges commonly encounter three primary challenges in the practical teaching of their relevant courses^[5].

2.1 The training site is limited by terrain and production conditions, which hinders access to the actual environment of the mountain orchard

The dispersed plots, steep slopes, and narrow roads hinder the entire class of students from accessing the actual orchard to conduct systematic practical activities. Even when access is granted, various constraints, including farming seasons, weather conditions, and production safety, limit the ability to repeatedly engage in the full closed-loop process of "design, installation, commissioning, and troubleshooting".

2.2 The procurement, operation, and maintenance costs of high-end equipment are prohibitively high, rendering the use of actual equipment for teaching purposes challenging

The international high-end mountain and hillside drip irrigation system, exemplified by Israel's Netafim company and featuring a comprehensive water and fertilizer integration system, can be priced as high as one million dollars. The cost of domestic acquisition is also substantial, making it challenging for schools to procure such systems in large quantities for student assembly and disassembly training. Conversely, low-cost equipment frequently lacks essential teaching observation points, including pressure compensation and intelligent control mechanisms.

2.3 The practical training content is divided into single functional modules, hindering the ability to provide comprehensive training on the entire process flow

The "terrain adaptation-communication networking-decision control-cloud operation and maintenance" processes of the irrigation system involve an extensive chain that integrates multiple disciplines, including mechanics, electronics, and IoT. Most traditional training rooms consist of single-function experimental benches, limiting students to local aspects and preventing them from developing a global perspective. There exists a substantial discrepancy between the skills acquired through such training and the professional competencies required for tasks such as "installation, debugging, and operation

and maintenance"^[6].

The essence of the above-mentioned problems can be attributed to the structural contradiction between the inherently high cost, elevated risk, and complexity of replicating real hilly agricultural environments, and the demands of practical training in higher vocational colleges, which require "repeated practice, comprehensive process coverage, and low-cost operation"^[7]. To address this contradiction, it is necessary to develop a practical training system design that can effectively integrate the "real scene" into the classroom at minimal cost while accurately reproducing the "real process" for students.

Virtual-real fusion training currently is an effective approach to addressing the challenges associated with agricultural equipment training, specifically "the inability to access real scenarios, afford actual equipment, and fully practice real processes". The underlying logic is well-defined: virtual simulation is employed to manage high-risk, high-cost, and difficult-to-replicate links; semi-physical platforms facilitate interface connections, joint debugging, and assembly and disassembly procedures; and real scenes are utilized for verification and application stages. The significance of this approach lies not only in the technological advancements, but also in its integration of region-specific crop operation scenes, vocational education skill formation principles, and actual production standards into the design of the practical training system.

However, existing research has not yet fully realized this objective. Domestic virtual simulation practices mainly focus on general agricultural machinery or single agronomic processes, exhibiting limited regional adaptation. In contrast, international studies tend to emphasize safety training, technical validation, or performance evaluation, but often lack comprehensive teaching modules tailored for vocational college students^[8]. More importantly, most approaches have failed to effectively integrate the "virtual-real" layers and have not developed a quantifiable system for assessing skill acquisition.

3 System design

3.1 Overall architecture The system employs a comprehensive architecture characterized by "four layers and one closed loop". From the bottom to the top, these layers comprise the virtual simulation layer, the semi-physical joint debugging layer, the real scene layer, and the teaching management layer. Together, these four layers establish a learning closed loop encompassing the stages of "design, implementation, verification, and evaluation", which is integrated with the teaching resource library via a unified data interface.

3.1.1 Virtual simulation layer. Based on the concept of the digital twin, an integrated simulation environment encompassing hilly terrain, pipeline hydraulics, communication networks, and control strategies has been developed. This environment facilitates "precise calculation, clear visibility, and cost-effective experimen-

tation" in areas such as terrain mapping, pipeline hydraulic analysis, LoRa coverage simulation, and control algorithm configuration.

3.1.2 Semi-physical joint debugging layer. A detachable platform-based training device has been developed utilizing actual hardware components, including LoRa terminal nodes, pressure-compensating drippers, electromagnetic flowmeters, soil moisture sensors, fuzzy PID (Proportional Integral Derivative) controllers, and edge gateways. Communication between the virtual objects and the physical controllers is facilitated via OPC UA and MQTT protocols, enabling functionalities such as "connectivity, adjustability, and usability".

3.1.3 Real scene layer. Utilizing the 1 hm² intelligent experimental field established by an agricultural product planting cooperative in Boluo County, on-site verification and promotion are conducted through remote observation and real-time control to ensure that the system is "practical, stable, and suitable for widespread adoption".

3.1.4 Teaching management layer. A lightweight training management platform has been developed using a technology stack consistent with the project's cloud platform, specifically Vue.js, Node.js, and MySQL. This platform facilitates the distribution of training tasks, the collection of process data, the automatic evaluation of grades, and the management of fault libraries.

3.2 Practical training transformation of core technology modules

3.2.1 Terrain adaptive drip irrigation system module. The real technical solution of the project involves the development of a three-tiered pipe network hydraulic model grounded in fluid mechanics equations. This model simulates the conversion process of slope potential energy using specialized software, achieving a potential energy utilization rate exceeding 90%. Dual-mode pressure compensation drippers have been developed: in gentle slope areas, elastic silicone diaphragms adaptively deform to maintain flow fluctuations within 5%, while in steep slope areas, a micron-scale groove flow-limiting mechanism is employed to stabilize water output. The system incorporates an integrated three-tiered filtration process of mesh, disc, and centrifugation combined with a bionic shark skin microstructure designed to prevent clogging within the flow channels. This approach effectively addresses irrigation uniformity challenges on slopes of 30°, achieving a uniformity rate above 75% and reducing costs by more than 80% relative to international alternatives.

During the practical training transformation, the actual pipeline network is scaled down to a transparent acrylic frame at a ratio of 1 : 10. All essential components, including the three-tiered pipeline network, pressure stabilizing tank (operating at 0.25 MPa), dual-mode dripper, and three-tiered filter, are preserved and designed to be disassemblable. In the virtual layer, CFD software is employed to simulate the hydraulics of the scaled pipe network. Students are able to modify parameters such as slope, pipe diameter, and dripper spacing to observe correspond-

ing changes in flow rate. Initially, the process of "design-simulation-optimization" is conducted within the virtual layer. Subsequently, in the semi-physical layer, real pressure sensors and flow meters are utilized for validation, thereby establishing a closed loop of "virtual configuration-experimentation-comparison". This design directly aligns with the project's technological innovation focus on the "slope grading compensation mechanism, intelligent recognition of terrain slope, and automatic switching of flow channel mode", enabling students to gain a comprehensive understanding of the core learning content related to "terrain slope-flow channel mode-irrigation uniformity" during practical training.

3.2.2 LoRa wireless communication networking module. The project implements a star topology for the deployment of the LoRa wide area network. A central gateway, equipped with a 10 dBi omnidirectional antenna, is installed on the mountaintop, while terminal nodes are positioned at 50 m intervals. Standby power consumption is maintained below 30 μ A through the use of channel activity detection mode. A TDMA (time-division multiple access) protocol has been developed to prevent data collisions among multiple nodes, ensuring a communication success rate exceeding 90% across 1 500 m.

During the practical training transformation, a practical training area measuring 200 m $\times$ 200 m, characterized by hilly micro-terrain, should be established on campus. Within this area, 6–8 physical LoRa terminal nodes and a central gateway should be deployed. The students' tasks encompass the following: (i) measuring the received signal strength indicator (RSSI) and bit error rate under varying spread spectrum factors and terrain obstructions using a spectrum analyzer; (ii) configuring TDMA time slots and monitoring data collisions and retransmissions when multiple nodes operate simultaneously; and (iii) constructing a LoRa network simulation of equivalent scale within a virtual environment using NS-3 or OMNET++, followed by a comparative analysis of packet delivery rates between the simulation and empirical measurements. This module aims to develop students' practical networking skills in the IoT domain, emphasizing the processes of "measurement, configuration, and optimization".

3.2.3 Fuzzy PID water and fertilizer decision-making module. The real project utilizes the deviation of soil moisture content and its rate of change as inputs, with the solenoid valve opening degree as the output, to develop a fuzzy PID dual-mode controller. A fertilization model is established for the entire growth cycle of macadamia nuts (N–P–K ratio of 1 : 0.5 : 0.8 at the germination stage and 0.6 : 1 : 1.2 at the fruit expansion stage). By integrating an electrical conductivity (EC) sensor, the deviation in fertilizer solution concentration is maintained within $\pm 5\%$, thereby creating a closed-loop water and fertilizer linkage system driven by crop demand.

During the practical training transformation, a semi-physical object is constructed by a real soil moisture sensor (measuring moisture content and EC), a physical solenoid valve, and a fertil-

izer liquid ratio tank. The controller utilizes STM32 + FreeRTOS to implement a fuzzy PID control algorithm. Student tasks include: (i) developing a fuzzy PID control model in MATLAB/Simulink and performing parameter tuning; (ii) programming the tuned parameters into the STM32, interfacing with the actual sensor and actuator, and observing the step response curve; and (iii) modifying the parameters corresponding to different crop growth stages (specifically, the NPK at germination and fruit expansion stages) and analyzing the fertilization model's tracking performance relative to the crop's water requirement pattern. This module aligns directly with the technical approach of the project, which focuses on "introducing adaptive fuzzy control algorithms in the decision-making level and dynamically optimizing irrigation strategies based on multi-dimensional environmental parameters", thereby cultivating students' competencies in intelligent control engineering encompassing "modeling, configuration, and validation".

3.2.4 Cloud-edge collaboration platform operation and maintenance module. The front-end of the project solution utilizes Vue.js to visualize the status of mountain pipeline networks. The back-end, developed with Node.js and MySQL, is capable of supporting thousands of concurrent users. Key functionalities include real-time display of pressure and flow, issuance of second-level response instructions by the irrigation decision engine, and proactive early warnings generated by the fault diagnosis center. The mobile terminal supports command issuance on Android devices, automatic synchronization of local storage with network recovery for 7 d offline control strategies, and edge-cloud collaboration to reduce monthly data traffic to 50 Mb.

During the practical training phase, students are granted access to the read-only API of the project's cloud platform as well as a test account for the mobile APP. The students' responsibilities encompass configuring equipment ledgers, setting alarm thresholds, and generating water usage statistical reports within the practical training management platform. In addition, they should simulate abnormal conditions such as sensor failures and communication interruptions to perform fault diagnosis and recovery procedures. Furthermore, students operate the mobile APP in offline mode and monitor the automatic synchronization between the local policy cache and the network upon reconnection. This module is designed to develop students' competencies in the operation and maintenance of agricultural IoT platforms, focusing on the processes of "configuration, monitoring, and maintenance".

3.3 Practical training management platform The platform utilizes the same technology stack as the project cloud management platform, specifically Vue.js, Node.js, and MySQL, while incorporating specialized teaching functionalities. These include a template library for practical training tasks, process data collection, automatic score evaluation, and fault library management^[9]. The platform is capable of supporting thousands of concurrent users, thereby accommodating the requirement for an entire class to engage in online practical training simultaneously.

4 Teaching application plan

4.1 Three-tiered progressive practical training process The system organizes practical training teaching into three progressive stages: "virtual, semi-real, and real". Each module adheres to a sequence comprising "virtual simulation design, semi-physical joint debugging and verification, and real scene transfer", alongside a mechanism that "synchronizes research and teaching"^[10].

4.1.1 Virtual simulation layer. Students complete terrain mapping, pipeline hydraulic simulation, LoRa coverage simulation, fuzzy PID parameter tuning, and cloud platform configuration simulation within the computer laboratory. This layer emphasizes "encouraging students to experiment and learn from errors", allowing them to repeatedly adjust variables such as slope, SF, and PID parameters until the desired standards are achieved, without causing any wear or damage to consumables or equipment. This segment occupies approximately 40% of the total practical training hours.

4.1.2 Semi-physical joint debugging layer. Students complete practical activities involving real LoRa node networking, integrated sensor-controller-actuator debugging, and conducting water and power supply tests within the pipeline network on the training room platform. This layer emphasizes the development of "hands-on skills", requiring students to disassemble and assemble actual components, solder communication cables, program control units, and interpret sensor data. This segment constitutes approximately 40% of the total practical training hours.

4.1.3 Real scene layer. Students visited a 1 hm² experimental field managed by an agricultural product planting cooperative in Boluo County to engage in on-site instruction. During this practical session, they completed tasks including real terrain mapping, layout of actual drip irrigation heads, system integration debugging, and fault detection. This layer emphasizes the concept of "promotion", aiming to ensure that the knowledge acquired in the classroom is directly applicable to real-world field conditions. This segment accounts for approximately 20% of the total practical training hours.

4.2 Assessment and evaluation design The assessment employs a combined approach consisting of process evaluation (60 points) and result evaluation (40 points). The process evaluation is based on a comprehensive score derived from the virtual layer simulation compliance rate, the success rate of semi-physical joint debugging, and the on-site performance and operational data of the real layer. The result evaluation focuses on the final comprehensive practical training, wherein students are organized into groups to complete the entire closed loop process, "from terrain mapping to system integration debugging", culminating in the development of an operational mountain drip irrigation control scheme. Teachers assess the outcomes according to established project acceptance criteria, including irrigation uniformity of at least 75%, water-saving rate of at least 30%, communication success rate exceeding

90% , and controller response time within 8 sec.

5 Analysis of application effects

The system, following evaluation within the Horticulture Technology and IoT Application Technology majors at Huizhou Engineering Vocational College, has demonstrated accomplishments in three distinct areas.

5.1 The cost of practical training has decreased significantly

The conventional "whole-orchard field attachment" model necessitates renting an orchard, employing technicians, and incurring equipment depreciation costs. The average training expense per student is approximately 800 yuan per semester. This system utilizes a virtual layer to manage high-risk and high-cost links, a semi-physical layer that reuses detachable and assemblable benches, and a real layer that shares project test fields. Consequently, the average of per-student training cost has been reduced to approximately 240 yuan per semester, representing a reduction of about 70% .

5.2 The full-process capability training has been implemented

Prior to the implementation of the pilot program, students were typically limited to operate on a single experimental platform. Following the introduction of the pilot program, the majority of students are capable of independently executing the entire closed-loop process, which includes terrain mapping, pipeline network design, LoRa networking, fuzzy PID tuning, and cloud platform operation and maintenance.

5.3 Research and education collaboration feeds back to project development

The LoRa coverage measurement data collected by students offered additional samples to enhance the optimization of the project's communication scheme. The student teaching assistants facilitated the cooperative's engagement with farmers through targeted training sessions, successfully training 10 new-generation farmers and establishing a regional service station. These efforts met the project's objectives and provided tangible, measurable feedback for practical training and teaching.

6 Conclusions

This article examines the practical challenges encountered by agricultural higher vocational colleges in the agricultural equipment training within hilly regions, specifically "the inability to access real scenarios, afford actual equipment, and fully practice real processes". Utilizing the municipal-level science and technology plan project of Huizhou Engineering Vocational College, titled "Research and Promotion of Integrated Application of Internet of Things Drip Irrigation Technology in Mountain Planting", as a technical blueprint, the study proposes a three-tiered, progressive training system that integrates virtual and physical components: "virtual simulation, semi-physical joint debugging, and real scene verification". The system has implemented practical training

transformations across four core technical modules integral to the project's research and development: terrain-adaptive drip irrigation, LoRa coverage over 1 500 m, fuzzy PID water and fertilizer decision-making, and a cloud-edge collaborative platform. These modules have been closely integrated with the project's research and development progress to realize a model of "synchronous research and teaching". Pilot applications indicate that the system has reduced practical training costs by approximately 70% , substantially improved the compliance rate of students' full-process closed-loop capabilities, and effectively supported the training of project farmers while advancing social benefit objectives. This initiative offers a practical training reform pathway characterized by "real project-driven, real data training, and real scene transfer" tailored for agricultural higher vocational colleges in hilly agricultural regions, demonstrating strong potential for replication and broader application.

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