J. Electrical Systems 20-3 (2024): 4713-4716

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Research on the Application of Digital Twin Technology in Water-saving Irrigation for Hillside Orchards: Achieving Precision Management Based on UAV 3D Modeling and Intelligent Algorithms

Journal of Electrical Systems

Abstract: - This paper aims to investigate the application of digital twin reality models in water-saving irrigation for hillside orchards. By constructing digital twin models of orch ards, precision and intelligent management of irrigation systems are achieved. Taking a kiwifruit orchard in the Karst mountainous region of Guizhou as the research object, this study utilizes unmanned aerial vehicles (UAVs) and 3D modeling to construct a site model of the study area. By integrating precipitation data over the past five years and the water storage patterns during the kiwifruit growth cycle, the irrigation strategies of the target orchard are analyzed. On this basis, the construction methods, application process, and effect evaluation of digital twin reality models in water-saving irrigation for hillside orchards are elaborated . Experimental results indicate that digital twin reality models can significantly enhance the precision and efficiency of orchard irrigation, effectively improving water use efficiency of fruit trees without compromising photosynthetic efficiency, thereby providing robust support for the sustainable development of hillside orchards.

Keywords: digital twin, reality model, hillside orchard, water-saving irrigation, precision agriculture

I. INTRODUCTION

As a vital component of agriculture, hillside orchards hold significant importance in promoting rural economic development and ensuring food security [1,2]. Nevertheless, irrigation management in these orchards has long been a bottleneck constraining their growth. Factors such as rugged terrain and poor soil water retention capabilities render traditional irrigation methods incapable of precise water application, leading to substantial water waste [3,4]. Additionally, improper irrigation exacerbates issues like soil erosion and nutrient loss, impacting the ecological environment and sustainable development of orchard [5]. Hence, exploring an efficient and precise irrigation management approach is paramount to the advancement of hillside orchards.

Digital twin technology, an avant-garde digital technology[6], constructs virtual models of physical entities to enable real-time monitoring and intelligent analysis of their operational states [7]. By applying digital twin technology to irrigation management in hillside orchards, precise simulation and intelligent control of the irrigation system can be achieved, thereby enhancing irrigation efficiency, mitigating water waste, and improving the orchard's ecological environment [8]. Consequently, research on the application of digital twin reality models in water-saving irrigation for hillside orchards possesses significant practical implications and broad application prospects.

Hillside orchards pose significant challenges in irrigation management due to complex terrain and varying soil conditions, often resulting in severe water waste and low irrigation efficiency [9,10]. With the rapid development of agricultural technology, digital twin technology, as an emerging digital management tool, has demonstrated immense application potential in the agricultural sector [11]. By constructing virtual models of physical entities, digital twin technology enables precise simulation and real-time monitoring of their entire lifecycle, offering novel solutions for agricultural production management [12]. This paper explores the application of digital twin reality models in water-saving irrigation for hillside orchards.

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II. Construction Methods of Digital Twin Reality Models in Water-saving Irrigation for Hillside Orchards

A. Data Collection and Preprocessing

Data collection serves as the foundation for constructing digital twin reality models. Various sensors deployed within the orchard capture real-time data such as soil moisture, rainfall , and crop growth status [13]. To ensure data accuracy and reliability, preprocessing steps including data cleaning, denoising, and calibration are essential.

B. Model Construction and Simulation

Based on data collection and preprocessing, computer-aided 3D modeling techniques are utilized to construct a digital twin reality model of the hillside orchard using UAV-captured aerial images. The model encompasses information on the orchard's terrain, soil distribution, crop types and distributions, and irrigation facilities [14,15]. Through simulation analysis, changes in soil moisture and crop growth status under different irrigation schemes are simulated, providing a basis for subsequent irrigation decisions.

C. Intelligent Decision-making and Optimization

Optimal irrigation decision schemes are formulated using intelligent algorithms based on simulation results. These schemes comprehensively consider factors such as soil moisture, crop water requirements, and rainfall , achieving precision and intelligent irrigation [16,17]. Additionally, irrigation decision schemes are continuously optimized based on actual orchard conditions and irrigation effectiveness feedback, enhancing irrigation efficiency and water-saving effects.

III. Application Process and Effect Evaluation

A. Application Process

In practical applications, the constructed digital twin reality model is deployed into the orchard irrigation management system. Real-time data from the orchard updates the model' s status information dynamically. Simulation analysis is utilized to model orchard state changes under various irrigation schemes, and optimal irrigation decisions are formulated based on intelligent algorithms. These decisions are then transmitted to the irrigation control system for execution, with real-time monitoring and feedback adjustments.

By utilizing a self-contained GPS-equipped drone to capture standard aerial photographs of the orchard, and subsequently employing 3D modeling software to arrange these aerial images in a point cloud configuration, thereby constructing a digital terrain model of the orchard.

In digital modeling of the orchard, elevation information is extracted by utilizing the aerial image positioning information obtained from a self-contained GPS-equipped drone, with a focus on capturing the distribution of irrigation density.

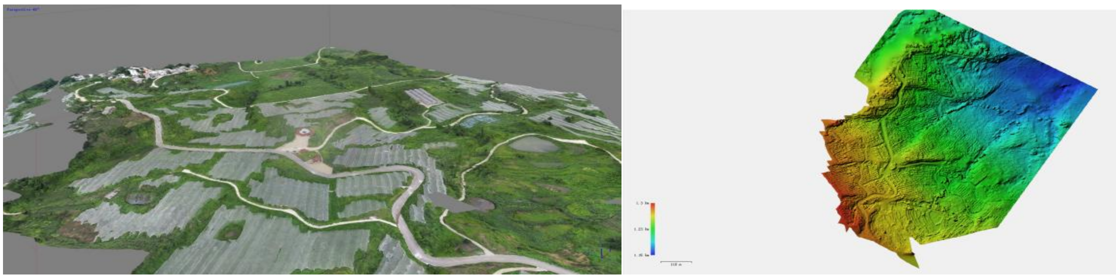

Figure. 1 Digital model of hillsid orchard and extraction of irrigation gradient

Figure. 2 Collection of meteorological and fruit growth dynamic data

To enhance the scene information within the digital model of the actual orchard, we employ real-time meteorological sensor devices to synchronously record non-visual scene information, such as meteorological data comprising temperature, atmospheric humidity, wind force, and solar irradiance. This ensures that the digital model captures and incorporates a comprehensive range of environmental factors that influence the orchard's conditions and fruit growth dynamics.

Synchronize the collection of fruit tree growth dynamic information through real-scene monitoring and non-destructive physiological observation equipment to realize the parameters of the digital twin model for mountain orchard production.

B. Effect Evaluation

Table. 1 Water demand of kiwifruit trees during different growth stages in the experimental area

Budbreak/mm	Flowering period/mm	Fruit growth/mm	Fruit maturation/mm	Phenological phase/mm
132.79	46.41	521.235	91.56	791.995

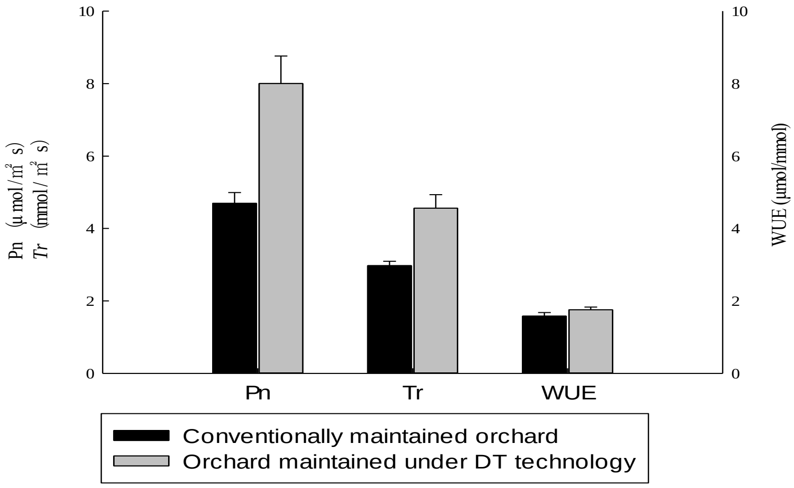

Figure. 3 Photosynthetic growth and water use efficiency of fruit trees under different management practices (Pn:Net photosynthetic rate, Tr: transpiration rate, WUE: water use efficiency

To evaluate the application effects of digital twin reality models in water-saving irrigation for hillside orchards, a comparative experiment was designed. Two similar orchard plots were selected as experimental and control groups. The experimental group utilized digital twin reality models for irrigation management, while the control group adopted traditional irrigation methods. Irrigation water consumption, crop yield, soil moisture, and other indicators were compared between the two groups. Experimental results showed that the orchard managed with digital twin reality models reduced irrigation water consumption by approximately 10%, with Greater growth vigor.

IV. CONCLUSION AND OUTLOOK

This paper explored the application of digital twin reality models in water-saving irrigation for hillside orchards. By constructing and applying digital twin models to irrigation management, precision and intelligent control of irrigation systems were achieved. Experimental results demonstrate that digital twin reality models can significantly enhance irrigation precision and efficiency, reduce water waste, and improve orchard ecosystems. With the continuous development and improvement of digital twin technology, its application in agriculture will become more extensive and profound. Future research can further explore the deep integration of digital twin technology with artificial intelligence and the Internet of Things [18], providing more comprehensive and robust support for the sustainable development of hillside orchards.

ACKNOWLEDGMENT

The authors acknowledge the financial support from Collaborative Horizontal Technology Project: 'Integration and Demonstration Research on Standardized Cultivation and Management Techniques for Cost-Saving and Efficiency-Enhancing Kiwifruit Production.

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