DEVELOPMENT AND PERFORMANCE EVALUATION OF AN INTERACTIVE VIRTUAL SIMULATION PLATFORM FOR MECHANIZED PEPPER HARVESTING BASED ON UNITY 3D

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基于 Unity 3D 的辣椒机械化收获交互式虚拟仿真平台的开发与性能评估

Zhiqiang SONG [1, 2], Xiang DU [1], Jie YU [1], Shuyun LIN [3], Yunxiang YE [*2, 4]

[1] School of Agricultural Engineering, Jiangsu University, Zhenjiang, Jiangsu / China;
[2] Key Laboratory of Agricultural Equipment for Hilly and Mountainous Areas in Southeastern China (Co-construction by Ministry and Province), Ministry of Agriculture and Rural Affairs, Hangzhou, Zhejiang / China;
[3] Guizhou Institute of Mountain Agricultural Machinery, Guiyang, Guizhou / China
[4] Zhejiang Academy of Agricultural Sciences Agricultural Equipment Research Institute, Hangzhou, Zhejiang / China

Tel: +8619741702769; E-mail: yeyx@zaas.ac.cn; Corresponding author: Ye Yunxiang

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ABSTRACT

This study used SolidWorks to create a chili harvester model, 3ds Max to create planting terrain and chili plant models, and developed a virtual simulation platform for chili harvesting experiments based on Unity 3D. Finally, the feasibility of the virtual simulation platform was confirmed through human-machinery interaction effects and virtual simulation harvest experiments, which can provide reliable training and research data, solve the drawbacks of on-site training and testing, and contribute to the sustainable development of China's chili industry.

摘要

本研究应用 SolidWorks 创建辣椒收获机模型，应用 3ds Max 创建种植地形和辣椒植物模型，以及基于 Unity 3D 开发了一款的辣椒收获实验虚拟仿真平台。最后，通过人机交互效果和虚拟仿真收获实验证实了该虚拟仿真平台的可行性，能够提供可靠的训练和研究数据，解决了场地培训、试验的弊端，有助于中国辣椒产业的可持续化发展。

INTRODUCTION

China has been an agrarian society since ancient times, with a continuous history of farming and animal husbandry spanning over ten millennia. Throughout the extended period of traditional agricultural economy, ancestors created a splendid farming civilization through their diligence and wisdom *(Peng et al., 2011)*. Against the backdrop of China's comprehensive rural revitalization and accelerated modernization of agriculture and rural areas, it is of significant practical importance to provide mechanical harvesting training for agricultural engineering students and new-era professional farmers. By conducting harvest training experiments on crops, it can cultivate students' passion for agriculture, enhance the skills of new-era professional farmers, and accelerate the translation of agricultural machinery R&D achievements into field applications *(Liu et al., 2023)*.

However, field experiments for pepper harvesting face limitations such as seasonal constraints, farming cycles, and weather dependencies, resulting in prolonged timelines and high costs. To address these challenges, this study developed a virtual simulation platform for pepper harvesting experiments based on Virtual Reality (VR) technology.

In recent years, with the rapid advancement of computer and information technologies, virtual reality (VR) technology has emerged as a powerful tool grounded in computational systems. Leveraging its immersion, interactivity, and simulation capabilities, VR has been successfully implemented across diverse domains such as industry, agriculture, medicine, military, and education. The progress in VR has further facilitated the digitization and visualization of operational processes, offering innovative solutions to challenges in experimental training and practical applications *(Seth et al., 2011)*.

Both domestic and international researchers have conducted numerous explorations in utilizing VR technology to showcase cultural heritage and disseminate traditional culture.

For instance: *Zhang et al. (2011)* from Beijing Forestry University employed VR technology to design and implement a virtual landscape of the Northern Song Dynasty imperial gardens; *Liu et al.(2010)* from Northwest University reconstructed a 3D digital model of the Small Wild Goose Pagoda from the Tang Dynasty by acquiring point cloud data; *Chen Yan et al. (2019)*, *Wang Jianxiang et al. (2022)* developed a virtual simulation platform for mechanized corn harvesting based on Unity 3D respectively, conducting harvest simulation experiments under various conditions such as different operating speeds and plant densities. *Liu et al. (2014)* established a virtual testing platform for sprinkler irrigation vehicles using Unity 3D and *Li et al. (2017)* created a virtual demonstration platform for ancient Chinese farming scenes based on Unity 3D. Other similar research has been conducted by *Cheng et al. (2018),* who studied the performance of combined forest harvesters through a Unity 3D-based virtual training system; *Lü et al. (2015)* developed a virtual fruit tree pruning platform using Unity 3D and *Cheng et al. (2018)* designed a virtual exhibition platform for agricultural culture based on Unity 3D.

The aforementioned studies demonstrate that numerous scholars and experts in China have conducted extensive research on virtual reality technology. Developing virtual simulation platforms based on virtual reality technology can effectively demonstrate operational processes, showcase cultural and product features, and exhibit market potential. Among these, Unity 3D, as an engine for virtual reality system development, can create high-quality 3D virtual simulation environments with immersive experiences. By using the C# scripting language to develop control programs, it enables interactive behaviors between objects, revealing the principles of their interactions *(Yan et al., 2013; Liu et al., 2014).* This provides valuable references for the related research in this paper.

Although numerous researchers have developed virtual simulation platforms using VR technology, no existing studies have specifically addressed interactive virtual simulation for pepper harvesting operations. As the world's leading producer and consumer of peppers, with cultivation widespread across China's agricultural regions, peppers represent both a nutritionally valuable vegetable containing unique bioactive compounds and a significant cash crop for natural pigment extraction *(Zhang et al., 2021; Du et al., 2023)*. Given this agricultural importance, the present study establishes pepper as the target crop for developing an interactive virtual simulation platform of mechanized harvesting processes using Unity 3D. This innovative platform will not only simulate the complete mechanized harvesting workflow but also enable comprehensive performance evaluation of pepper harvesting machinery *(Wang et al., 2024)*.

MATERIALS AND METHODS

Structure of pepper harvesters

The pepper harvester consists of several key components: a picking device, conveying mechanism, cleaning and separation mechanism, collection bin, chassis, power transmission system, and hydraulic control system. Fig. 1 illustrates the schematic diagram of a typical pepper harvester structure. The key components are numerically labeled as follows: *1*. spring-tooth drum picking device, *2*. operator control cabin, *3*. primary conveying system, *4*. operator seat, *5*. engine and power transmission assembly, *6*. cleaning and re-picking device, *7*. secondary conveying system, *8*. auto-discharging collection bin, *9*. crawler-type traveling mechanism, *10*. belt pulley assembly, *11*. sprocket-chain transmission set.

Among these components, the picking device serves as the most critical part of the pepper harvester, as shown in Fig. 2. The key components are numerically labeled as follows: *1.* steel frame, *2.* upper cover plate; *3.* shield cover plate; *4.* left side plate; *5.* driving shaft; *6.* imitate terrain roller; *.7* left divider; *8.* spring finger cylinder; *9*. roller for bending branches; *10*. right divider. It performs dual functions of combing and conveying peppers, directly determining the machine's overall harvesting efficiency and quality *(Song et al., 2024)*.

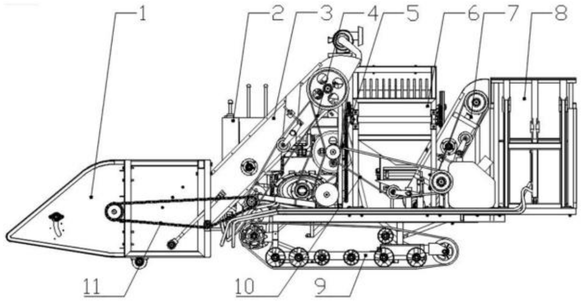


Fig. 1 - Schematic diagram of pepper harvester structure

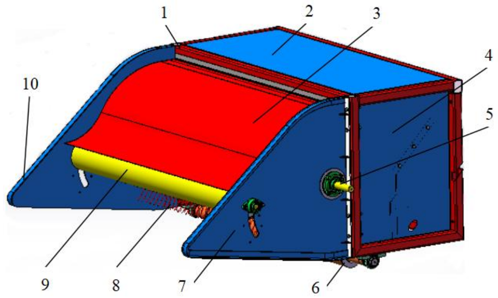


Fig. 2 - Structure model of pepper picking device

Working principle of pepper harvesting

During field harvesting operation, the pepper harvester advances forward with its picking device. The terrain-following wheels maintain continuous ground contact, providing stable support for the picking assembly. The pressure roller first bends the taller pepper plants to an optimal harvesting angle for spring-tooth drum picking. The spring-tooth drum rotates clockwise at 180-220 rpm, with the flexible teeth executing a combined action of impact detachment, frictional removal, and combing collection. Then, the peppers picked attain an initial velocity, and the subsequent trajectory controlled by its gravity acceleration, aerodynamic resistance, and the guide baffle's surface geometry. Then, the chili peppers enter the primary conveyor along the rotating path of the drum for next process under the interaction of multiple factors *(Du et al., 2024; Zhou et al., 2024)*. Fig. 3 schematically illustrates this dynamic harvesting process.

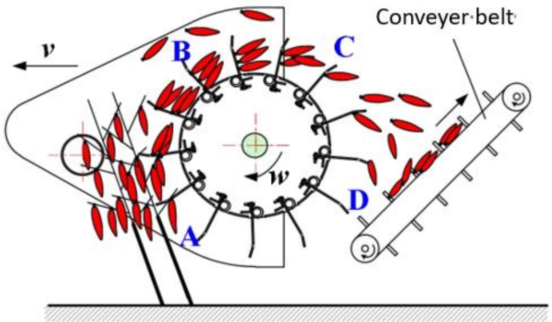


Fig. 3 - Schematic diagram of spring-tooth drum pepper picking mechanism

Development logic of virtual simulation platform

The virtual simulation platform for mechanized pepper harvesting was developed using Unity 3D within a Client-Server (C/S) architectural framework. As shown in Fig. 4, the system implements a structured five-layer architecture consisting of model layer, data layer, service layer, development layer, application layer. This hierarchical architecture offers several technical advantages: modular system design enabling component-based development, clear functional decoupling between layers, scalable infrastructure for future capability expansion, distributed computing support through C/S architecture.

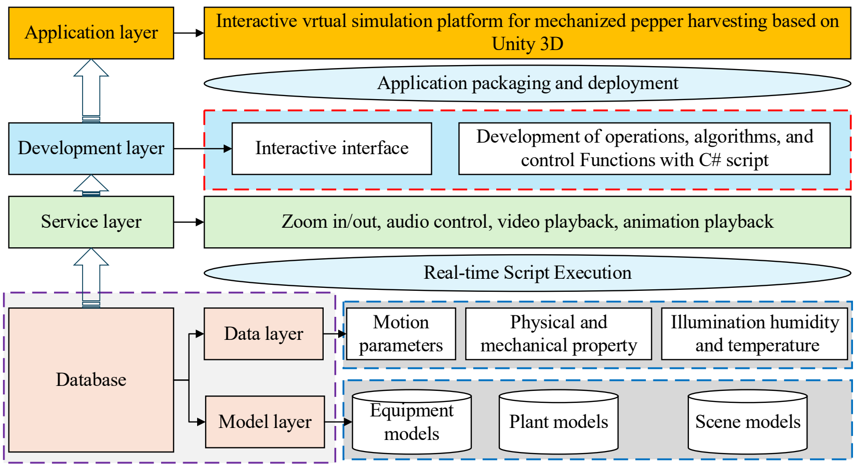


Fig. 4 - Hierarchical structure diagram for development of the virtual harvest simulation platform

The model layer provides basic resources for the virtual harvest simulation system, including virtual models of chili harvesters, chili plant models and environment models designed by 3D modeling software such as SolidWorks and 3D Max *(Xiang et al., 2014)*. Data layer is used to manage agricultural datasets and operational parameters. The service layer is used to make real-time calls to the model library and database, enhancing the performance of the simulation system, such as configuring animation playback, interface zooming in and out, background sound, etc.

The development layer is located between the service layer and the application layer, and is the central hub of the system, including control programs edited in C # language, statistical algorithms for harvesting chili peppers, view stitching algorithms, and other script files, as well as human-machinery interaction interfaces. The data collected by the application layer can be sent to the service layer, and the data feedback from the service layer can be sent to the application layer for display.

The application layer is located at the outermost layer of the entire system, which packages the various modules of the system logically and hierarchically before publishing the application program, thus forming a set of application programs with functions such as interface display, human-machinery interaction, and data input.

Structural framework of the virtual simulation platform

Based on the working principles of pepper harvesters and the development logic of virtual simulation platforms, the structural framework of the mechanized pepper harvesting virtual simulation platform is shown in Fig. 5. The virtual simulation platform consists of six core modules, which are interface & perspective observer, pepper harvester model manager, pepper plant models manager, environment observer, models base, and database.

Interface & perspective observer is used to provide user interaction and multi-angle visualization by setting the camera follows mode. Pepper harvester model manager is used to provide configurable component models for harvesters, such as picking device model, material conveying mechanism model, walking mechanism model, and steering system model. Pepper plant model manager is used to provide chili plant virtual model and planting patterns. The harvesting operation environment model includes sunlight, sky, fields, trees, buildings, etc. Model base stores 3D component models. The database is used to store various characteristics and motion parameters of chili harvesters, harvest data, as well as various parameters of chili plants.

In addition, to achieve an interactive virtual simulation platform for mechanized harvesting of chili peppers, rigid body properties and physical collision functions should be added to the virtual models, and script files should be edited using C # language in the Unity 3D development environment.

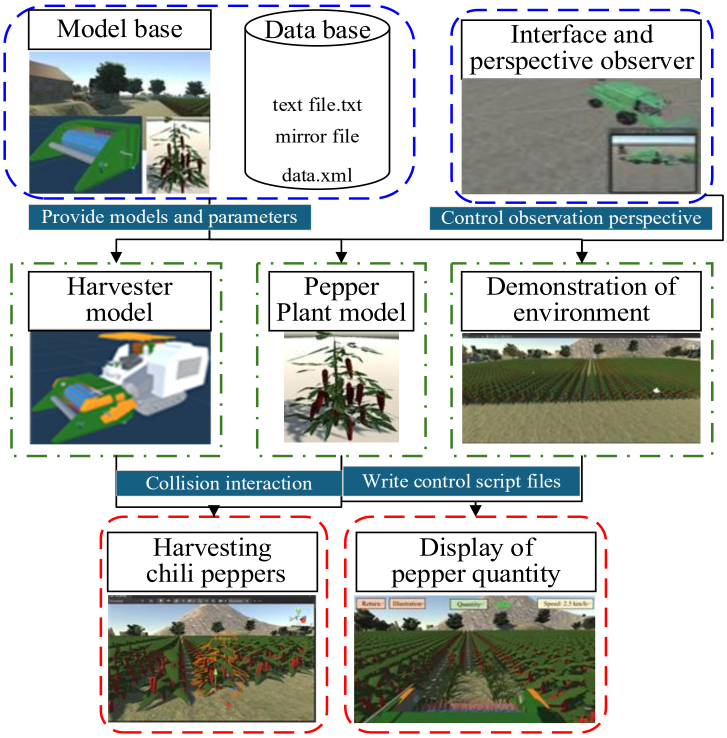


Fig. 5 - System architecture diagram of chili harvesting virtual simulation platform

Technical process of virtual simulation platform development

Development of the virtual simulation platform follows the relevant technical development flowchart, as illustrated in Fig. 6. Firstly, collect relevant data of the pepper harvester, pepper plants, and virtual harvesting scene, create 3D models using SolidWorks and 3D Max, followed by optimization, rendering, and unit/size format conversion; Secondly, import the constructed models into Unity 3D software for editing, and create a virtual farm scene using the Terrain component in Unity 3D software. Once again, design rigid body components and collider components for the constructed models to enable physical interactions, and add sound and animation playback, write application programs, and implement the relevant functions and harvesting tasks of the virtual harvester. Finally, generate the application software and conduct relevant virtual simulation experiments.

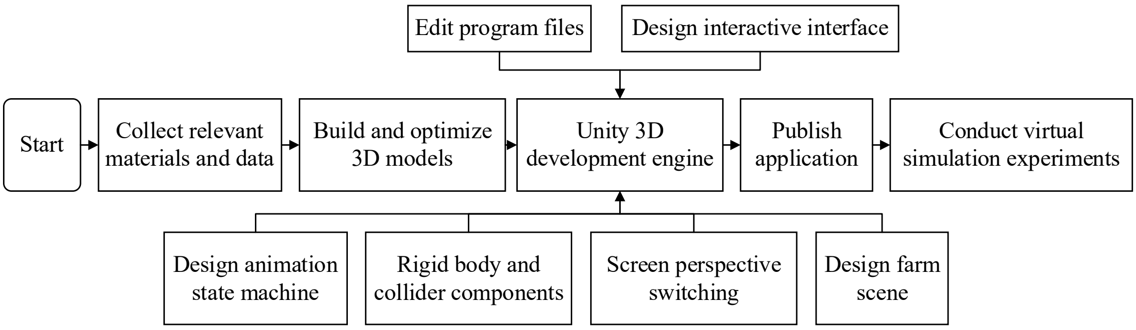


Fig. 6 - Relevant technical development flowchart

Development of virtual simulation platform

Under the structural framework of the interactive virtual simulation platform, adhere to the technical workflow for virtual simulation platform development to develop 3D virtual models for each component, design the UI interactive interface, integrate attribute components, and design control strategies and corresponding programs, thereby realizing the interactive functions of the virtual simulation platform and achieving the simulation effect of chili pepper mechanized harvesting.

Virtual model of chili harvester

Taking a certain chili pepper harvester as a reference, a three-dimensional model of the pepper harvester was established using SolidWorks, the key components include picking device, material conveying mechanism, cleaning and separation mechanism, aggregate box, walking mechanism, and hydraulic control system, as illustrated in Fig. 7. Among them, the picking device is the core harvesting component for pepper, consisting of spring teeth and roller. The 3D model was then imported into 3D Max for texture rendering and optimization before being exported in .fbx format for compatibility with the simulation platform.

Virtual model of pepper plants

A three-dimensional model of peppers and pepper plant was established based on relevant parameters of chili peppers, as shown in Fig. 8. To optimize performance and reduce computational load, the model underwent texture mapping and rendering in 3D Max, then exported as an .fbx file for importing into Unity 3D.

Construction of terrain model

The virtual farm terrain was constructed using Unity 3D's built-in Terrain Toolkit, enabling realistic topographical features such as elevation variations, soil textures, and crop row layouts. Key parameters (e.g., field size, slope gradient) were calibrated to match real-world harvesting conditions, as shown in Fig. 9.

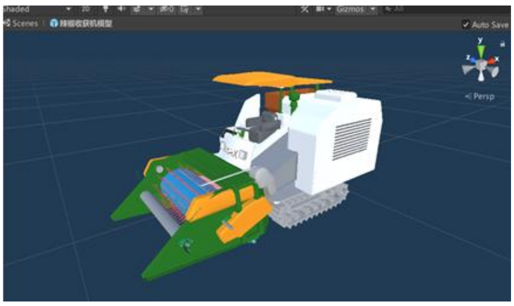


Fig. 7 - Virtual model of pepper harvester

Fig. 8 - Pepper plant model

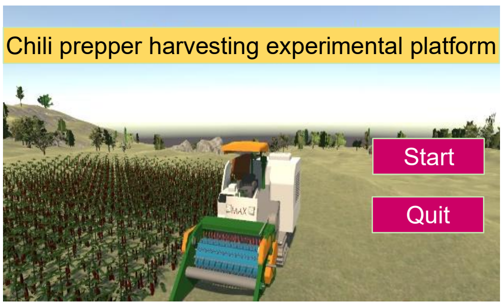


Fig. 9 - Terrain model

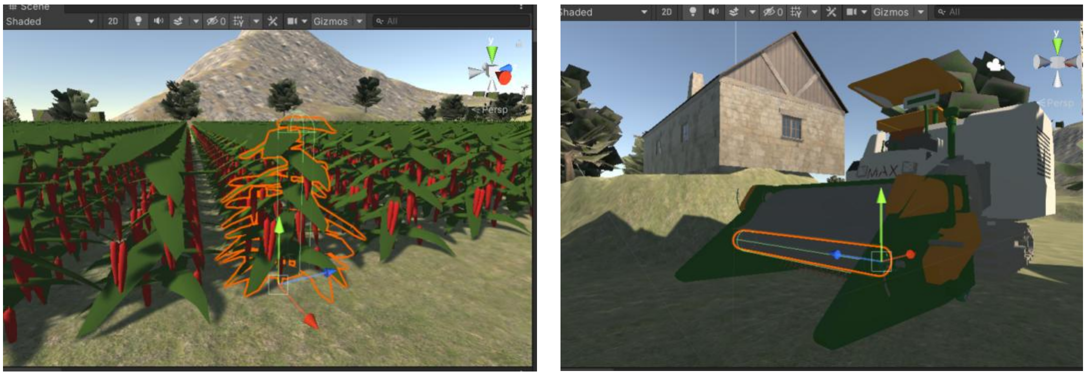
Configuration of rigid body and collider properties

To accurately simulate the physical interactions between the chili pepper harvester and pepper plants within the virtual environment, rigid body and collider components were assigned to both models. This implementation ensures the pepper harvester and pepper plant models adhere to Newtonian motion laws, enabling authentic collision responses (e.g., plant displacement during harvesting), *(Wu et al., 2018)*.

There are six types of colliders provided by Unity 3D software to simulate physical interactions: Box Collider, Sphere Collider, Capsule Collider, Wheel Collider, Terrain Collider, and Mesh Collider. Each type of collider is strategically implemented based on its unique characteristics. Box Collider is applied to the harvester body for optimal performance due to its simple geometry, low computational overhead, and fast processing speed. Mesh Collider is utilized for high-precision collision detection, matching the complex geometry of the cutting surface with accurate mesh representation.

Wheel Collider is implemented for realistic wheel physics, featuring integrated collision detection, physical parameters, and a slip-based tire friction model. Terrain Collider is assigned to the field plot to provide ground physical properties and support all 3D models within the scene, to avoid model penetration (e.g., harvester falling through terrain) *(Wang et al., 2022)*. Capsule Collider is custom-fitted to both the chili pepper plant model and toothed roller model to enable accurate collision detection during harvesting operations, as shown in Figures 10 (a) and 10 (b).

This script executes the picking action when the toothed roller interacts with chili peppers, ensuring realistic harvesting behavior.



a) b)

Fig. 10 - Configuration of collider components

a) Collider configuration for the chili plant model; b) Collider configuration for the toothed roller

Animation state machine

An animation state machine is a control system designed to manage the sequential or conditional transitions between discrete animation states of a character or object. By partitioning complex animation sequences into modular, action-specific segments (e.g., "idle," "walk," "attack"), it enables dynamic state transitions triggered by in-timeline events, user inputs, or programmatic logic. Widely adopted in game development and interactive applications, this system streamlines animation control by defining states (distinct animation phases) and transition rules (conditions for switching between states), ensuring efficient, scalable, and maintainable animation pipelines.

The process of mechanized harvesting of chili peppers includes multiple animation states such as users getting on a harvester, starting the engine, adjusting the height of the cutting table, adjusting the operating speed, controlling the movement of the harvester, and picking chili peppers. Therefore, the animation can be controlled and serialized using the functions of the animation state machine, achieving modular editing and improving the maintainability and reusability of the control code.

The design process of an animation state machine is as follows: Firstly, complete the entire animation process of operating the chili harvester using 3D Max software, and focus on the start and end frames of each animation segment for each operating state. Then, group the "*.fbx*" format files according to their animation states and divide them into animation segments. Drag and drop the divided animation clips to the already created state machine to assign attributes and create animation transition lines. Write relevant code programs to drive trigger functions on the timeline, so as to enable an animation to be called at a certain time node and complete the transformation of the animation.

First-person navigation and view control

To enhance user immersion and experience, a first-person navigation system has been applied in the virtual environment. The first-person navigation system enables users to freely explore the scene and control their viewing perspective through intuitive keyboard and mouse inputs. Create script files within the character controller to manage movement and viewpoint rotation. Implementation details include configuring appropriate motion parameters (such as speed, gravity, etc.), using the W/S keys to control forward and backward movement, A/D keys to control left and right steering, and Q/E keys to control vertical movement (up/down). Right-click and drag to activate 'View Control' for adjusting the camera's rotation and orientation.

This implementation provides users with an intuitive and immersive navigation experience while maintaining optimal performance within the virtual environment. The system can be easily modified to accommodate different movement styles or control schemes as needed.

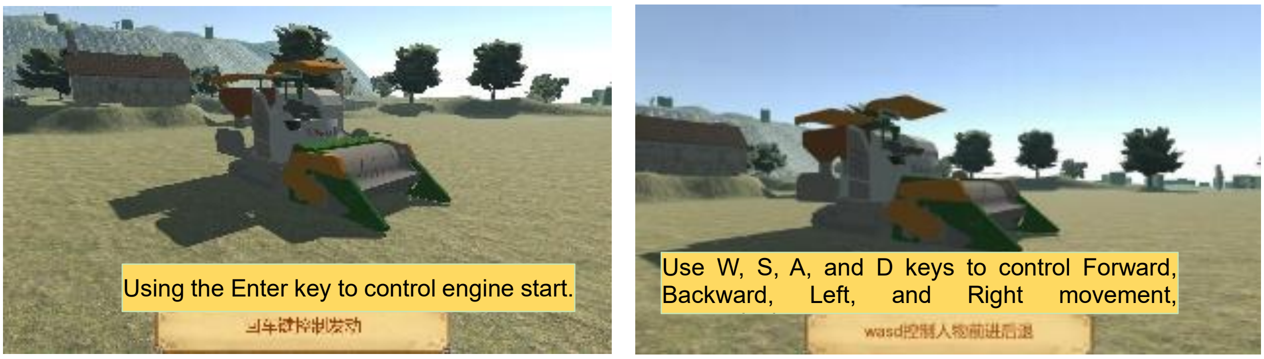
Design and implementation of UI Interface

A human-computer interaction system was designed through the graphical user interface (GUI) in Unity3D, utilizing the built-in UI system for optimal functionality and user experience. In order to ensure the user experience of the UI interface, the creation of UI components, button configuration, visual design parameters, interactive functions, and other aspects need to be carefully designed. The implementation process included the creation of a hierarchical UI structure consisting of a main control panel, function-specific submenus, and a status display area. Each button was configured with multi-state visual settings, event listeners for click actions, associated sound effects, and tooltip information for hover events. Interaction handling was implemented using Unity's EventTrigger component, custom C# scripts for complex interactions, and animation controllers to provide smooth transitions.

RESULTS

Human- harvester interaction operation effect

Upon logging into the PC-based virtual simulation platform, users can engage in practical simulation operation training. When a user is outside the chili pepper harvester, the W, S, A, and D keys on the keyboard enable control of the user's movements, supporting forward, backward, left, and right turns. Upon reaching the proximity of the virtual chili pepper harvester model and pressing the F key (designated as the "boarding" action), the user enters the harvester's cab. At this point, the control target shifts to the harvester itself, transitioning to a first-person perspective for direct operation of the pepper harvester model. Then, the engine can be started by pressing the "Enter" key on the keyboard, accompanied by a realistic "rumbling" startup sound (Fig.11 a). Following engine ignition, movement control - forward, backward, left, and right-is enabled via the W, S, A, and D keys, delivering an immersive operational experience that closely mimics real-world harvester work (Fig.11 b).



a) b)

Fig. 11 - Control of the motion state of the virtual pepper harvester

a) Engine start; b) Harvester movement: forward, backward, left/right steering

The virtual simulation results demonstrate that the mechanized pepper harvesting simulation platform effectively supports human-machine interaction, confirming the feasibility of the proposed design.

Demonstration and analysis of the effect of pepper harvest experiment

Within the UI interactive interface, clicking the "Experiment" button activates the chili harvesting experiment module. From a first-person perspective, users perform pre-operation preparations such as adjusting the picking device height above the ground and shifting gears. Once the harvester is started, users can switch to a third-person perspective to observe the machine's working process in the field. Movement control (forward/backward/left/right) is managed via the W, S, A, and D keys on the keyboard. When the spring teeth on the picking device make contact with chili plants, the fruits are harvested while the plant stems remain intact on the ground. Meanwhile, the graphical user interface (GUI) dynamically displays real-time statistics of harvested chili fruits. Figure 12 illustrates the pre- and post-harvest scenarios of chili plants, visually demonstrating the efficiency of the picking process.

a) b) c)

Fig. 12 - The state before and after harvesting chili peppers
a) Before harvest; b) Choose walking speed; c) After harvest

A comprehensive series of virtual harvesting simulation experiments were conducted to evaluate system functionality and operational validity under varying operating speeds and drum rotation speeds. These virtual harvesting simulation experiments validated that the virtual simulation platform for mechanized pepper harvesting can execute harvesting experiments according to preset parameters and align with actual harvesting principles. These results confirm the platform's effectiveness as both a training tool and a research platform for optimization pepper harvesting.

CONCLUSIONS

This study successfully developed a virtual simulation platform for mechanized chili pepper harvesting based on Unity 3D. During the simulation platform development phase, detailed 3D models of chili harvesters, chili plants, and their operational environments were constructed. Functional control script files were programmed using C# to enable human-machine interaction simulations and virtual harvesting experiments under diverse conditions.

Experimental results validated the rationality of the design of virtual simulation platform and the correctness of the code governing overall machine movement. In addition, trainees provided feedback that the platform helps them carefully observe the harvesting process, understand the working principle of the harvester, and gain an immersive operating experience, thus confirming that the platform authentically simulates real-world field harvesting operations.

Although this research has achieved phased milestones, several limitations require further improvement. For instance, future work will focus on developing a flexible stem model with elastic properties to better simulate the stress dynamics during the picking process. Additionally, enhancing interaction rules through behavioral reasoning will improve the realism of virtual harvester-chili plant interactions, enabling more lifelike simulations of plant and fruit motion. Furthermore, conducting multi-factor, multi-level orthogonal experiments under varied conditions will help analyze the impacts of key parameters (e.g., operational speed, drum rotation) on harvest loss rate, net harvest rate, and damage rate. These advancements will provide critical references for optimizing harvester design and manufacturing processes.

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