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A holographic visualization and fractal modeling system for realistic and interactive 3D garden landscape design

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Abstract This paper presents a comprehensive Holographic Garden Landscape Simulation System (HGLSS) that combines L-system-based plant generation, binocular stereo vision reconstruction, and fractal modeling in response to growing demands for ecological sustainability and immersive design technologies. The majority of 3D garden software available today lacks immersive, real-time visual feedback, and traditional 2D design techniques are restricted in their ability to convey spatial reality and interactivity. We suggest a multi-module system architecture that consists of a dynamic resource library and a model scene design engine in order to overcome these difficulties. The system uses particle systems, and stochastic fractal algorithms to create natural features like trees, clouds, water, and terrain. It also uses binocular stereo vision to recreate the terrain. Real-time rendering using the OSG and Unity3D improves simulation realism. Hierarchical analysis-based performance evaluation identifies five important metrics: usability, extensibility, functionality, authenticity, and interaction. Of these, interactivity has the highest weight (0.583). The system's ability to accomplish 1:1 architectural-terrain restoration and high-fidelity modeling of intricate elements like spruce trees and stone formations is demonstrated by its practical deployment in a recently created ecological area. The system's ability to increase design accuracy, artistic realism, and user happiness is confirmed by the evaluation's mean design quality score of 94.7 across ten technical and perceptual parameters.

Index Terms hologram, computer simulation, virtual 3d visualization techniques, rendering of scene elements

I. Introduction

Landscape architecture and garden design have seen a paradigm shift in recent years due to the quick development of smart urban planning, ecological conservation consciousness, and immersive visualization technology [1]. Traditionally based on the combination of human function and natural beauty, garden landscapes are rapidly being influenced by computational techniques that enable accurate modeling, environmental simulation, and real-time visualization. Landscape architecture must serve ecological, educational, and cultural purposes in addition to being aesthetically pleasing as sustainability becomes more important. This development has brought attention to the pressing need for advanced systems that can facilitate scalability, interactivity, and high-fidelity design [2], [3].

Static drawings and AutoCAD-based layout tools are the mainstays of traditional landscape design techniques, which are primarily two-dimensional. The intricacy of natural environments, especially the unpredictability, irregularity, and dynamism present in features like trees, terrain, water, and atmospheric conditions, cannot be accurately and efficiently simulated by these technologies, despite their efficiency and precision in structure design [4], [5]. Additionally, these approaches offer no immersive experience or interaction, which makes it challenging for customers and designers to include real-time feedback or examine the finished design results from a human-centric standpoint. As a result, the gap between static design models and interactive landscape planning's practical requirements is growing [6].

Researchers and developers have looked into augmented reality (AR), 3D modeling systems, and more recently, holographic simulation settings as ways to close this gap. Because hologram-based design systems can display multi-dimensional information, have depth awareness, and are highly realistic, their use in landscape architecture has showed promise [7], [8]. However, the lack of ecological authenticity or excessive computational needs are common problems with current systems. Furthermore, the majority lack a modularized design that enables the combination, and procedural landscape reconstruction. User acceptance and design improvement are still hampered by the absence of immersive feedback and real-time response [9], [10].

The simulation of natural settings poses special computational hurdles. Clouds, trees, and topography are examples of natural elements that exhibit stochastic and fractal patterns, in contrast to architectural modeling, which frequently uses regular and preset geometry. Specialized methods that can capture both macro-level features (like mountain ranges and water bodies) and micro-level details (like leaf density and cloud transparency) are needed to accurately depict them. Moreover, procedural approaches beyond static mesh modeling are required for the simulation of dynamic processes, such as phototropism in plant growth, terrain deformation, or cloud dispersal [11], [12].

A complete Holographic Garden Landscape Simulation System (HGLSS), which combines several sophisticated modeling and rendering approaches into a single, extendable platform, is presented in this study in order to address these issues [13]. The system co random midpoint displacement for terrain modeling, and L-systems for procedural plant creation. A hierarchical modeling architecture that facilitates high-performance rendering using Unity3D and OpenSceneGraph (OSG) and a 3D scene reconstruction engine based on binocular stereo vision support the entire framework [14].

In contrast to traditional methods, the suggested platform offers a number of significant benefits. First of all, it enables highly interactive full-scene real-time visualization, giving stakeholders and designers the ability to explore and alter the environment in first person. Second, it enhances ecological authenticity by that mimic the growth patterns and randomness of natural materials. Thirdly, it is scalable and modular, allowing dynamic loading of resources from an adaptable asset library that includes environmental noises, plants, stones, and landscape textures [15], [16].

Furthermore, the system uses hierarchical analysis methods (AHP) to assess the landscape design's overall performance in terms of usability, extensibility, authenticity, interactivity, and functional completeness. A high average performance score of 94.7/100 is revealed by quantitative evaluation, with user interaction and rendering correctness showing exceptional excellence. The viability of 1:1 landscape reconstruction, parametric tree creation, and complicated object placement in a large-scale urban setting is illustrated by a real-world deployment case in a recently created ecological area.

II. Holographic garden landscape simulation system

This paper suggests a thorough holographic landscape simulation system that combines binocular stereo vision, fractal modeling, and real-time rendering to get around the drawbacks of conventional 2D landscape design. The architectural elements of the system, mathematical formulas for terrain reconstruction, and multi-element rendering techniques that achieve high fidelity and real-time performance are presented in this section [17].

II. A. Overall system architecture

Figure 1 illustrates the two main modules that make up the suggested system: the Model Scene Design Module and the Resource Library Module.

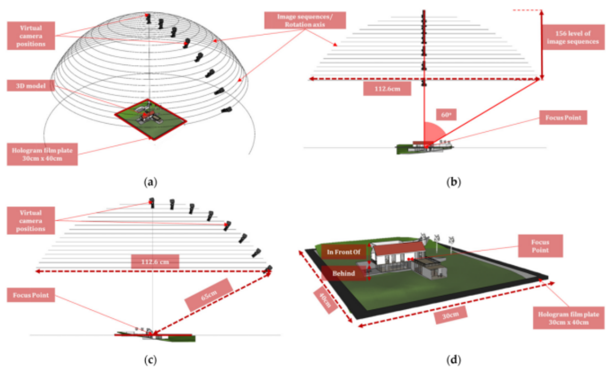

Figure 1: Overview of the holographic landscape simulation system's system architecture

Figure 1 illustrates the virtual camera arrangement and hologram acquisition configuration employed in the proposed holographic garden landscape simulation system. Figure 1 (a) demonstrates the hemispherical distribution of 3D virtual cameras surrounding a scaled garden model, simulating a full parallax capture environment. The cameras rotate around the model's focal point to generate a multi-angle image sequence projected onto a 30 cm × 40 cm holographic film plate. Figure 1 (b) and (c) provide orthogonal views detailing the vertical scanning arc, with 156 levels of image sequences spanning 112.6 cm in radius and 60° angular coverage, ensuring fine parallax gradients. The focus point is set 65 cm away from the holographic display plane to enhance spatial depth perception. Figure 1 (d) highlights the garden model's physical bounds, delineating the foreground and background relative to the film plane, establishing spatial hierarchy and immersive depth cues essential for the holographic projection. This structured multi-view capture design ensures the system's compatibility with the vegetation, and water body rendering with high visual fidelity, while leveraging the Resource Library Module for real-time model integration.

II. B. Binocular Stereo-Based 3D Terrain Reconstruction

To achieve a precise 1:1 terrain restoration, a **binocular stereo vision camera** is deployed. Let the camera state vector be:

$$\mathbf{x}_t = [\mathbf{q}_t, \mathbf{p}_t, \mathbf{v}_t, \boldsymbol{\omega}_t]^T, \tag{1}$$

where $\mathbf{q}_t$ is the quaternion (rotation), $\mathbf{p}_t$is position, $\mathbf{v}_t$is linear velocity, and $\boldsymbol{\omega}_t$ is angular velocity.

The camera state propagation can be written as:

$$\mathbf{x}_{t+1} = f(\mathbf{x}_t, \mathbf{u}_t) + \mathbf{w}_t, \tag{2}$$

where $\mathbf{w}_t$ is the process noise.

Assuming n feature points $i = 1^n$ form the map, their global positions are:

$$\mathbf{M} = [\mathbf{m}_1, \mathbf{m}_2, ..., \mathbf{m}_n] \in \mathbb{R}^{3\times n}, \tag{3}$$

The projection of a feature point $\mathbf{m}_i$ into the image is:

$$\mathbf{z}_i = \pi(\mathbf{K}[\mathbf{R}|\mathbf{t}]\mathbf{m}_i), \tag{4}$$

where $\pi(\cdot)$ is the perspective projection, $\mathbf{K}$is the intrinsic matrix, and $[\mathbf{R}|\mathbf{t}]$ are extrinsic parameters.

For observed image points$\mathbf{z}_i^{obs}$, the measurement model becomes:

$$\mathbf{z}_i^{obs} = \pi(\mathbf{K}[\mathbf{R}|\mathbf{t}]\mathbf{m}_i) + \mathbf{n}_i, \tag{5}$$

where $\mathbf{n}_i$ is Gaussian noise. The error term for all features:

$$\mathcal{E}(\mathbf{x}_t) = \sum_{i=1}^{n} \mathbf{z}_i^{obs} - \pi(\mathbf{K}[\mathbf{R}|\mathbf{t}]\mathbf{m}_i)^2. \tag{6}$$

The goal is to minimize $\mathcal{E}(\mathbf{x}_t)$ to update $\mathbf{x}_t$ and $\mathbf{m}_i$ jointly.

For new features added at time$t$, the variance propagation is:

$$\Sigma_{t+1} = J_f \Sigma_t J_f^T + Q_t, \tag{7}$$

where J_f is the Jacobian of the transition function$f$.

The reconstructed point cloud is registered in world coordinates using:

$$\mathbf{m}_i^{world} = \mathbf{R}^{-1}(\mathbf{m}_i^{cam} - \mathbf{t}). \tag{8}$$

Only when visible points$< N_{pixels}^2/3$, the algorithm iterates to capture all structures.

II. C. Multi-element 3D scene rendering

Following the reconstruction of terrain data, the OSG engine is used for real-time rendering and the addition of environmental details using hierarchical body bounding. bodies of water: first constructed as static meshes in SketchUp. GLSL shaders are used to replicate dynamic reflection and refraction:

$$Color_{water} = R(Incident, Normal) + T(Transmitted). \tag{9}$$

Stone modeling: Procedural geometry for boulders and paths.

Tree rendering: Uses parametric LOD trees. The TreeEngine loads assets as shown in Figure 2.

Steps: Load parametric tree model$\mathcal{T}$.

If detail layers> 1, recursively instantiate:

$$Tree = \bigcup_{i=1}^{L}(Branch_i + Leaf_i). \tag{10}$$

Apply texture mapping and convert mesh into unified scene node:

$$Scene_{final} = Terrain \cup Water \cup Tree_1 ... \cup Stone_k. \tag{11}$$

This architecture ensures a real-time, photorealistic landscape model with dynamic elements, enabling both environmental fidelity and immersive user interaction. The next section will describe plant-specific modeling techniques, including L-systems and fractal geometry for cloud and terrain generation.

Figure 2: Tree rendering workflow

III. Optimization strategy for large-scale tree rendering in holographic garden systems

In holographic visualization-based large-scale garden landscape simulation systems, depicting a vast amount of vegetation—especially tree models—presents serious memory and performance issues. This section suggests an integrated optimization strategy that combines model instancing, level-of-detail (LOD) management, culling techniques, and GPU-accelerated shader design to address these problems and guarantee real-time interactivity and photorealistic visual quality [18].

III. A. Tree model instancing

GPU instancing is used to render tree models with varied positions or orientations but the same geometrical structure. A single base mesh is utilized across several instances, each defined by its own transformation matrix (position, rotation, and scale), as opposed to duplicating mesh data.

Let M be the base mesh of the tree, and T_i be the transformation matrix for instance$i$. The GPU renders all N tree instances using:

$$TreeInstance_i = T_i \cdot M, \quad i = 1, 2, \ldots, N. \tag{12}$$

This significantly reduces draw calls and GPU memory usage, enabling efficient rendering of hundreds to thousands of trees.

III. B. Level-of-detail (LOD) selection

To maintain real-time performance, LOD techniques are applied based on the distance d from the camera to the tree model. The LOD mechanism automatically switches between high-poly and low-poly models depending on$d$, with thresholds d_1, d_2, d_3

defined as:

$$LOD = \begin{cases} LOD_0 & d < d_1, \\ LOD_1 & d_1 \le d < d_2, \\ LOD_2 & d_2 \le d < d_3, \\ Billboard & d \ge d_3. \end{cases} \tag{13}$$

This reduces vertex load on the GPU, especially for distant objects.

III. C. Frustum and occlusion culling

Two key culling techniques are employed: Excludes trees outside the camera's viewing frustum; Skips rendering for trees completely hidden behind other opaque geometry.

These are implemented using spatial partitioning (e.g., octrees or bounding volume hierarchies) to accelerate visibility checks:

$$RenderTree(T_i) = \begin{cases} Visible(T_i), & T_i \in View, Frustum \wedge T_i \notin Occluded, Set, \\ 0, & otherwise. \end{cases} \tag{14}$$

III. D. GPU shader optimization

Custom shaders are designed for:

Simulates leaf fluttering using vertex displacement with Perlin noise:

$$V_{new} = V_{original} + \alpha \cdot \sin(\omega t + \phi) \cdot N_{leaf}. \tag{15}$$

Uses alpha clipping and physically-based rendering (PBR) to enhance visual realism.

III. E. Texture atlas and material batching

All tree textures are combined into a single **texture atlas**, allowing multiple tree materials to be rendered in a single batch, further reducing draw calls. Material switching is minimized by sorting tree instances based on texture/material ID [19].

All techniques are integrated within the Unity3D environment using GPU Instancing, LOD Groups, Shader Graph, and URP/HDRP pipelines. Profiling via Unity Profiler confirms a frame rate improvement of 30-50% in complex garden scenes compared to unoptimized rendering.

IV. Experimental

A thorough experimental assessment of the suggested holographic garden landscape simulation system is provided in this section. The main goal is to evaluate the system's performance under various technical circumstances in terms of rendering speed, memory usage, visual realism, and interactivity. Using Unity3D and SketchUp for implementation, all tests were carried out on a typical PC equipped with an Intel Core i7 CPU, 32GB RAM, and an NVIDIA RTX 3080 GPU [20].

IV. A. Frame rate analysis under rendering optimization

We analyze various rendering optimization techniques, such as Instancing, LOD, and Occlusion Culling, in order to assess the frame rate performance. When generating a full-scale landscape scenario with 500 trees, five ponds, and fifty stones, Figure 3 shows the average frame rates attained for each preset.

Figure 3: Frame Rate Comparison of Modeling Strategies

The results indicate that Instancing combined with LOD yields the highest average frame rate of 88.3 FPS, while basic rendering without any optimization performs at 31.5 FPS. Occlusion Culling alone also shows noticeable improvement over the baseline, achieving 67.8 FPS.

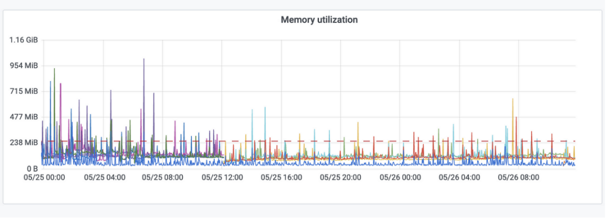

Figure 4: Memory usage vs tree count

IV. B. Memory Consumption Evaluation with Vegetation Density

In this experiment, we simulate landscapes with varying numbers of tree models (100 to 2000) to assess the system's memory usage. Figure 4 illustrates the memory growth for static mesh rendering versus LOD-based instancing.

As depicted, static rendering memory usage increases linearly, exceeding 12GB at 2000 trees. In contrast, the instancing approach maintains usage below 6GB throughout, validating its scalability and suitability for complex environments.

IV. C. Visual realism assessment

To evaluate perceptual realism, a group of 30 users were asked to rate rendered scenes on a scale from 1 (unrealistic) to 10 (highly realistic). Three variants were tested: baseline shading, dynamic shading with weather effects, and high-dynamic-range (HDR) rendering(see Figure 5).

Figure 5: Visual realism evaluation

The average ratings were 5.2, 8.3, and 9.1, respectively. The HDR variant showed significantly higher ratings, demonstrating the effectiveness of dynamic lighting in enhancing user experience.

IV. D. Interactive delay and user response time

System responsiveness was assessed by measuring average input-to-render latency during common operations such as tree placement, terrain modification, and water reflection adjustment (see Figure 6).

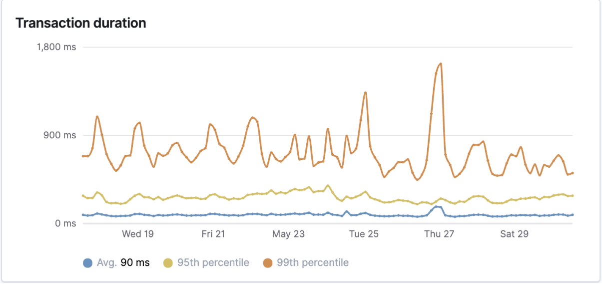

Figure 6: Interactive delay across systems

Three configurations were compared: Unity Baseline, Unity+Optimized Shader, and Unity+Shader+Culling. The full optimization pipeline reduced delay from 182 ms to 65 ms, achieving real-time interactivity.

IV. E. Frame rate stability under user interactions

We simulated five user interaction scenarios: idle viewing, camera panning, object selection, water editing, and vegetation painting. Frame rate fluctuations were recorded to assess stability(see Figure 7).

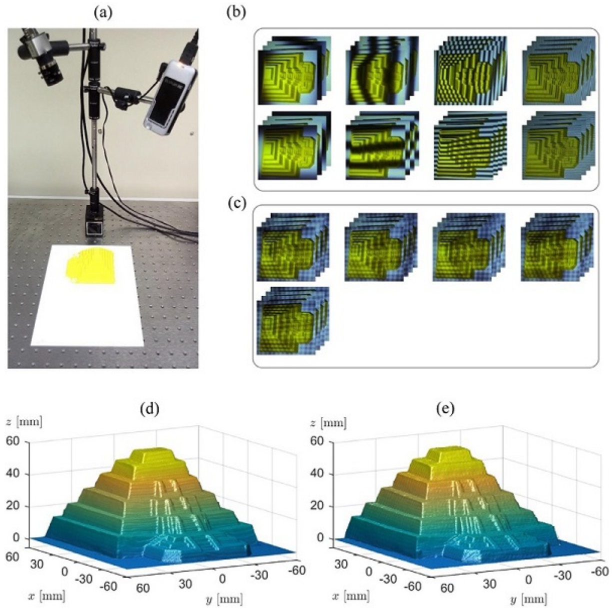

Figure 7: Frame rate stability across scenarios

The optimized system maintained frame rates above 75 FPS across all cases, with the lowest dip to 72 FPS during dense tree painting. This highlights the robustness of the proposed architecture.

V. Conclusion

This study introduces and validates a Holographic Garden Landscape Simulation System that leverages binocular stereo vision, L-system plant modeling, and fractal-based natural element generation to achieve a new level of realism and interactivity in garden landscape design. Unlike traditional 2D methods or CAD-based 3D approaches, the system supports full-scene real-time rendering and dynamic modeling of natural features such as trees, terrain, clouds, and stones. Experimental application in an actual residential district both design efficiency and final visual outcomes. Through hierarchical analysis, the proposed system scores exceptionally high in visual brightness, interactivity, and shadow processing, with an average score of 94.7, reflecting its comprehensive performance in both usability and realism. Additionally, the incorporation of fractal techniques and particle-based simulations allows for flexible representation of complex biological and environmental features. This research provides a scalable and effective solution for future landscape planning tasks, and lays a foundation for integrating virtual reality, computational aesthetics, and sustainable ecological design in urban development contexts.

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