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Research on Real-Time Intelligent Rendering Method for Immersive Interactive Virtual Reality Scenes

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Abstract: Virtual reality scenes oriented towards immersive interaction have strict requirements for real-time rendering, such as high frame rate, low latency, and visual consistency. Traditional rendering methods are difficult to ensure both real-time performance and immersive experience under limited computing resources. This article systematically explores the key technologies and implementation paths of intelligent rendering methods: firstly, it analyzes the rendering pressure bottleneck, multi view continuity, and visual dual constraints caused by immersive interaction; Furthermore, an intelligent rendering mechanism based on gaze point prediction, scene semantic modeling, and closed-loop resource allocation will be constructed; On this basis, adaptive strategies such as behavior driven detail level adjustment, dynamic and static differentiation processing, spatiotemporal consistency, and load coordination are proposed; Finally, the evaluation indicators, stability analysis, and scalability verification of real-time performance and immersion are discussed. This article provides a system framework for the theoretical construction and engineering implementation of intelligent rendering methods.

Keywords: Immersive interaction; Real-time intelligent rendering; Fixation point prediction; Adaptive level of detail

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1. Introduction

With the rapid development of virtual reality technology, immersive interaction puts extremely high requirements on real-time performance and visual authenticity of scene rendering, while the traditional graphics rendering pipeline is limited by fixed logic and limited computing capacity, making it difficult to simultaneously guarantee immersive experience and computational efficiency in high frame rate, low latency dynamic interactive environments [1]. Therefore, for virtual reality scenes oriented to immersive interaction, real-time intelligent rendering methods have become a research hotspot, the core of which lies in introducing intelligent perception, dynamic resource allocation, and adaptive strategies to break through existing rendering bottlenecks. This paper aims to systematically explore technical challenges in this field, construct an intelligent rendering mechanism oriented to immersive features, and also analyze scene adaptive strategies, thus exploring the path of balance between real-time performance and immersiveness, in order to provide a theoretical reference for subsequent research and engineering practice.

2. Immersive interaction poses technical challenges for real-time rendering

2.1. Rendering pressure bottleneck under high frame rate and low latency

Immersive interaction requires rendering frame rate to reach 90 FPS or higher, and end-to-end latency also needs to be below 20 milliseconds. Users are prone to dizziness and perceptual disorders, which places direct pressure on the traditional rendering pipeline, with available computation time per frame being compressed to approximately 11 milliseconds, and in high-resolution headsets, pixel filling and geometry processing volume grow exponentially. General rendering algorithms such as ray tracing or complex shading are difficult to complete full computation within this time window, thus forcing system to make trade-off between image quality and response speed, more importantly, unpredictability of interactive behavior further amplifies above pressure, when users suddenly turn their head or move, rendering system must regenerate complete view within an extremely short time, with insufficient precomputation buffer available [2]. And breaking through hard constraints of frame rate and latency has become a fundamental bottleneck that intelligent rendering methods must prioritize to solve.

2.2. Continuity requirements for multi-perspective and dynamic scenes

Immersive interaction not only requires high-quality rendering from a single viewpoint, but also needs to maintain spatiotemporal consistency among multiple viewpoints during user's continuous head movement, with viewpoint moving at speed of several meters per second, scene projection relationship between adjacent frames will undergo drastic changes, and any rendering inconsistency, such as shadow jumping, texture flickering and geometric misalignment, will be immediately captured by visual system, thereby destroying sense of immersion [3]. Moving objects in dynamic scenes further aggravate this challenge, as their positions, postures, and occlusion relationships change rapidly, which requires the rendering system to complete verification and update of multi-viewpoint consistency within an extremely short period of time [4]. Traditional methods based on inter-frame difference or simple interpolation are difficult to simultaneously meet the requirements of speed and continuity, thus producing motion ghosting or afterimages, with building a rendering continuity mechanism that supports smooth transition among multiple viewpoints being a prerequisite for achieving immersion.

3. Construction of an intelligent rendering mechanism for immersive features

3.1. Intelligent region refinement rendering based on gaze point prediction

Gaze point prediction technology, by tracking movement of user's eyeballs, estimates in real time center of attention in current field of view, and guides rendering resources to lean toward that region, with the human visual system having physiological characteristics, which determines that fovea is only highly sensitive to details within about 2 degrees of center of visual field, while peripheral regions show significantly increased tolerance for resolution, shadow precision, and texture details [5]. Intelligent rendering methods can cleverly utilize this characteristic, performing full-precision rendering in gaze point region, that is, high-resolution textures and precise lighting calculations, and gradually reducing sampling rate and shading complexity in peripheral regions, with the key lying in foresight of prediction algorithm, since rendering pipeline has inherent latency, thus requiring the system to predict landing point of gaze point several frames in advance, to avoid obvious resolution jumps when user turns their head [6]. Combined with positional encoding and attention mechanisms, deep learning plays an important role here, and the prediction accuracy of the gaze point can reach the sub-pixel level, thereby providing reliable support for region-refined rendering.

3.2. Perception sensitivity modeling based on scene semantics

Elements of different scenes contribute significantly differently to the immersive experience, and an intelligent rendering mechanism should dynamically adjust the rendering priority of objects according to the semantic category of objects. Semantic objects, such as dynamic characters, interactive objects, and text information, are often the focus of user attention, and their rendering defects (such as jagged edges, update delays, and missing shadows) are easily perceived. However, subtle degradation of distant backgrounds, static decorations, and repeated textures is not easily noticeable, while perceptual sensitivity modeling is a quantitative description of this difference, which decomposes 3D scene into a semantic map through pre-trained scene understanding network, and assigns sensitivity weights to each type of object, with this weight being not only determined by category of object, but also influenced by its spatial distance, motion state, and position relative to gaze point [7].

3.3. Dynamic trade-off logic between intelligent clipping and global features

Rendering resources are limited, and at this time, the intelligent clipping mechanism plays a role, which is responsible for identifying and removing visual information that contributes less to the sense of immersion, while retaining global features that are sufficient to maintain the understandability of the scene. Unlike traditional frustum clipping or occlusion clipping, intelligent clipping not only considers geometric visibility but also incorporates semantic importance and scene coherence constraints [8]. There is a small fast-moving object in distance, which can be temporarily clipped without attracting attention, but if object is only reference point indicating direction of movement, such as a flight guidance arrow, minimum visual presentation of it must be retained, with the logic of dynamic balance playing a core role in this process, thereby adjusting clipping threshold in real time according to currently available computing budget, complexity of scene, and user interaction state.

3.4. Closed-loop adaptive allocation between rendering tasks and computing resources

The resource allocation problem of real-time rendering is essentially an online optimization problem under dynamic constraints, which requires the construction of a closed-loop feedback system between rendering tasks and computing resources. The input of the system includes the rendering task queue for the current frame (each task comes with an estimated cost and priority), available GPU computing power, video memory bandwidth, and power consumption limit; The output end is task scheduling and resource allocation instructions [9]. The difficulty of closed-loop control lies in the strong coupling between task cost and resource state–high-priority gaze point rendering may occupy other tasks, leading to global frame time exceeding the limit. The intelligent allocation method adopts a cyclic architecture of prediction execution evaluation adjustment: based on historical frame data, it predicts the resource requirements of the next frame, evaluates whether the frame rate target is met after allocation, and if it deviates, the allocation strategy is corrected through a proportional integral derivative controller or a learning scheduler.

4. Scene adaptive rendering strategy under intelligent driving

4.1. Detail level strategy for real-time adjustment based on user interaction behavior

The core of the level of detail strategy is to use user interaction behavior as a direct trigger signal for rendering resource scheduling, rather than relying solely on scene geometric distance. Traditional LOD based on line-of-sight static mapping cannot reflect interactive intent–the object that the user is staring at and preparing to grab should maintain high accuracy even if it is far away, while distant non-interactive backgrounds can be greatly simplified [10]. Intelligent methods dynamically identify potential interaction targets and improve their LOD level in advance by analyzing interaction trajectories such as handle ray pointing, hand bone movement, or head approach speed. At the same time, an interaction urgency measure is introduced to enable expensive effects such as subsurface scattering and high-precision normal mapping for objects that are about to be touched, and conservative LOD is performed on areas with no signs of interaction in the near future.

4.2. Differentiated processing mechanism for dynamic objects and static environments

In the scene, there is a fundamental difference in rendering consistency between dynamic objects and static environments. Two have different needs for differentiated processing pipelines, static environments such as architecture and terrain have pre-computable properties, with their lighting information, along with shadow maps and global illumination caches being baked in advance and reused across multiple frames. In contrast, dynamic objects such as moving characters and interactive props need to recalculate their positions, poses, and real-time occlusion relationships with the environment every frame [11]. Intelligent rendering mechanism makes full use of this difference, allocating low-frequency update channels for static environments, thereby adopting lower refinement frequencies and coarser spatial sampling rates, allocating high-frequency update channels for dynamic objects to ensure smooth motion trajectories and no visual breaks at seams with static scenes. The core challenge lies in interactive lighting between dynamic objects and static environments. Dynamic objects cast moving shadows and also receive environmental reflections, which requires lightweight real-time global illumination approximation solutions (such as radiometric probes or screen space reflections) to maintain visual fusion between the two and avoid a ‘floating feeling’ that breaks immersive experience.

4.3. Intelligent collaboration of spatiotemporal consistency and instantaneous computing load

Spatiotemporal consistency requires that rendered results maintain smooth transitions between continuous time frames and adjacent spatial viewpoints, but this has an inherent contradiction with dynamic fluctuation of instantaneous computation load, when system detects that load is too high, it usually takes degradation measures, such as reducing resolution and turning off special effects, however if these operations suddenly change within single frame, they may cause visual flickering or texture jumping, thereby directly destroying spatiotemporal consistency [12]. Intelligent collaborative method solves this contradiction by introducing ‘smooth degradation corridor’, which sets multiple continuous visual quality levels, and difference between each level is progressive step that is not easily perceived by human eye, when load exceeds limit, system does not directly jump levels, but slides frame by frame along corridor to target level, with temporal anti-aliasing and motion vector compensation being combined to conceal traces of change, and vice versa, upgrading frame by frame as load decreases. In addition, the system also needs to estimate the load trend of future frames, thus avoiding frequent changes in quality levels caused by short-term peaks.

4.4. Rendering strategy and minimization model of immersive experience loss

The essence of any intelligent rendering strategy is to minimize the immersive experience loss perceived by users under computational resource constraints, requiring the establishment of formal loss functions and optimization frameworks. Define immersion loss as a weighted sum of multidimensional indicators, including visual fidelity loss (such as texture blur, shadow loss), temporal discontinuity loss (such as inter-frame flicker, motion drag), and interactive response loss (such as operation feedback delay). Each strategy action–adjusting LOD, enabling clipping, changing sampling rate–will result in different loss distributions in the aforementioned dimensions. The core of the minimization model is to find the optimal strategy combination for each frame, so as to minimize the total immersion loss under a given computational budget. Due to the large strategy space and non-convex loss function, traditional exhaustive search is not feasible.

5. Balance and verification path between real-time performance and immersion

5.1. Construction of evaluation indicators for real-time rendering performance and immersive perception intensity

The evaluation indicators should cover both the objective performance of the system and the subjective immersion experience of users. Objective indicators include frame rate, frame time variance, end-to-end latency, and rendering load utilization, which can be directly measured. The subjective immersion intensity needs to be calibrated through psychophysical experiments, such as using a dual task paradigm to measure the user's perception threshold of scene changes, or inferring the level of attention engagement through head movement trajectories and gaze point distributions. Suggest building a composite indicator called 'immersion maintenance rate', defined as the ratio of the user's continuous immersion time to the total usage time under given hardware constraints. At the same time, the ratio of perceived quality score to system overhead is introduced as an efficiency indicator to avoid unthinkingly pursuing high image quality and wasting computing power. The standardization of the indicator system provides a quantitative benchmark for subsequent algorithm comparisons.

5.2. Stability analysis of intelligent methods under different scene complexities

Intelligent rendering methods need to maintain stable performance in environments with significant differences in complexity, such as open terrain, dense urban scenes, and enclosed indoor spaces. The dimensions of stability analysis include frame rate fluctuation coefficient, rendering quality variance, and strategy switching frequency. Using the method of controlling variables: a fixed hardware platform is used to sequentially run the same intelligent algorithm in large-scale vegetation scenes, multi-dynamic character scenes, and high reflection material scenes, and record the degree of performance degradation in each scene. The analysis should focus on two failure modes: one is the strategy oscillation that occurs when the scene suddenly changes, manifested as frequent LOD level jumps; The second is the crashing degradation of the system after the complexity exceeds the threshold, that is, the frame rate drops sharply below the dizziness threshold. By extracting the correlation between feature parameters of different scenarios and algorithm performance, the applicable boundaries and vulnerable links of intelligent methods can be identified.

5.3. Threshold discussion on the impact of delay and visual feedback deviation on immersion

The disruption of immersion caused by delay and visual deviation has nonlinear characteristics and clear perceptual thresholds. Experimental studies have shown that users are almost imperceptible when the end-to-end latency is less than 15 milliseconds; 15 to 25 milliseconds can only be perceived in high dynamic motion; If it exceeds 30 milliseconds, it generally causes obvious discomfort and disconnection from operation. Visual feedback bias includes perspective drift, texture mapping misalignment, and motion ghosting. Its tolerance threshold is influenced by the type of bias and scene semantics: static bias can be ignored within a 0.5-degree perspective, while dynamic bias exceeding 0.1 degrees may be captured per frame. The discussion should further distinguish the different sources of delay–rendering delay, transmission delay, and display delay have different weights for disrupting immersion, with the former having the highest sensitivity. Determining these thresholds helps to set quantifiable engineering constraint goals for intelligent rendering algorithms.

5.4. Verification of scalability and cross-scene adaptability of intelligent rendering strategy

Scalability requires intelligent rendering strategies to maintain effective degradation rather than complete failure on heterogeneous computing platforms, from mobile VR to workstation level PC. The verification method adopts cross-platform comparative experiments: under the same algorithm framework, the maximum allowable frame time constraint is relaxed from 6 milliseconds to 25 milliseconds in sequence, and the upward curve of the immersion loss index is observed. The adaptability is verified through scenario transfer testing: the strategy trained in Class A scenarios is directly deployed to Class B scenarios, and the degree of performance degradation is measured. The ideal intelligent strategy should have zero sample generalization ability, which means it can maintain acceptable immersion quality in scenes of different geometric complexities, material features, and dynamic densities without retraining. If the attenuation is significant, meta-learning or domain adaptation modules need to be introduced to improve cross-scene robustness.

6. Conclusion

In summary, the core of the real-time intelligent rendering method for immersive interactive virtual reality scenes lies in breaking through the hard constraints of traditional rendering pipelines in frame rate, latency, and resource allocation, and establishing a dynamic optimization mechanism centered on user perception. Starting from the technical challenges of immersive interaction, this article analyzes the requirements of high frame rate, multi view, and visual style dual constraints on rendering systems; Furthermore, an intelligent rendering mechanism based on gaze point prediction, scene semantic modeling, and closed-loop resource allocation was constructed, and adaptive strategies such as behavior driven LOD adjustment, dynamic and static differentiation processing, spatiotemporal consistency, and load coordination were proposed. On this basis, an evaluation index system that includes objective performance and subjective immersion intensity is proposed, and the issues of delay threshold and cross-scene adaptability are discussed. Future research can further integrate brain-computer interfaces with generative AI to achieve more predictive and personalized immersive rendering.

Disclosure statement

The author declares no conflict of interest.

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