A Mixed Reality Framework for Interactive Realistic Volume Rendering with Dynamic Environment Illumination

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Abstract

Interactive volume data visualization using a mixed reality (MR) system is increasingly popular in the research and development field of computer graphics. Due to sophisticated requirements of user interaction and vision when using head-mounted display (HMD) devices, the conflict between the realisticness and efficiency of direct volume rendering (DVR) is yet to be resolved for MR applications. We develop an MR visualization framework that can support interactive realistic volume rendering and integrated it into a prototyping MR system. This MR system can display high-quality volume rendering effects that synchronously reflect dyanamic illumination of surrounding environment in real time. The comparative analysis shows that our MR visualization framework helps provide users intuitive perception of displayed volumetric structures as they naturally exist in the real-world environment.

Index Terms: Computing methodologies—Computer graphics—Graphics systems and interfaces—Mixed / augmented reality; Computing methodologies—Computer graphics—Rendering

1 Introduction

Mixed reality (MR) aims to composite rendered 3D models into real-world scenes. Compared to conventional monoscopic display techniques (e.g. the display of a mobile phone), MR viewing using a head-mounted display (HMD) device can better support intuitive user perception of 3D model structures. To provide interactive MR rendering results, existing MR solutions simply overlay rendering results of virtual models onto real-world scenes, and their rendering effects do not respond to the dynamically varying environment illumination. Compared to surface rendering, direct volume rendering (DVR) aims to retain detailed information of volume data and plays an important role in scientific visualization [4]. Realistic illumination facilitates producing high-quality shadowing and shading effects and helps users perceive depth information and spatial relationships of rendered volumetric structures [5]. Both DVR and realistic illumination are normally computationally expensive. Our work tries to enable interactive visualization of 3D volume data with dynamic realistic illumination in real-time MR applications.

We develop a realistic DVR framework that can be integrated into an interactive MR system. The rendering result of 3D volume data can reflect dynamic illumination synchronized with the surrounding environment in real time to improve user's immersive feeling during MR viewing. Our MR visualization framework and prototyping system have great potential to facilitate users exploring scientific volume data more intuitively in MR applications.

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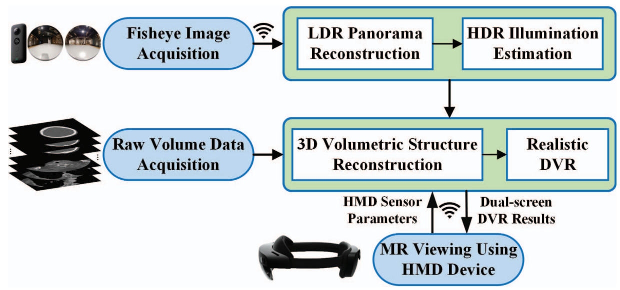

Figure 1: The pipeline of our MR visualization framework for realistic DVR with dynamically varying environment illumination.

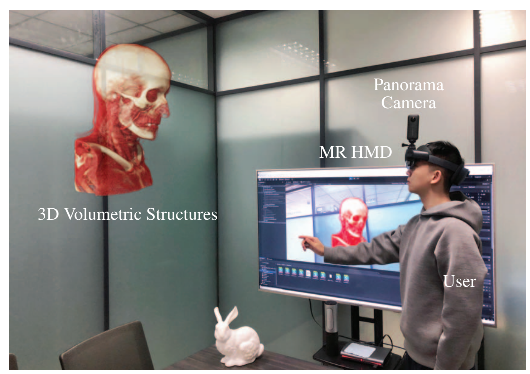

Figure 2: The spectator view of our MR prototyping system. A user can manipulate the displaying of volume data using an MR HMD.

2 Design of Our MR Volume Rendering Framework

The workflow of our MR prototyping system is demonstrated in Fig. 1. Photos of surrounding scenes are captured by a panorama camera and then transmitted to a PC via WiFi. The PC serves as a graphics workstation to perform complex computations. The first step is to accurately estimate the surrounding environment illumination that varies over time (Sec. 2.1). The second step is to efficiently perform a physically-based DVR of 3D volume data that can synchronously reflect dynamic environment illuminations estimated in real time (Sec. 2.2). Rendered frames of DVR are transmitted to an MR HMD via WiFi. The rendered volumetric structures can then be visualized as a real object existing in front of the user's eyes (Fig. 2).

2.1 Estimation of Environment Illumination

An LDR panorama camera with fisheye lenses is used to capture photos of the surrounding environment. Since HDR photo capturing is usually time-consuming and do not satisfy real-time MR applications, we do not use HDR cameras even though they can obtain accurate lighting information. LDR fisheye images captured are then transmitted to a PC workstation via WiFi for reconstructing low dynamic range (LDR) panoramas [2].

Since the LDR pixel bit depth is rather limited, important lighting information is commonly discarded. To compute realistic illuminations, we first perform illumination estimation to predict HDR environment map [1]. In practice, the rendered volumetric structures can be relocated anywhere in the world coordinate system via user manipulation. To satisfy spatially-varying illumination effects, we can refer to the relative position between virtual models and light sources to estimate the illumination from the position of the volume data, instead of from the panorama camera position. The reconstructed HDR illumination map is then used to provide omnidirectional lighting information for subsequent DVR.

2.2 Interactive DVR in MR

To allow rendering effects of volumetric structures reflecting dynamic surrounding environment illuminations, the Monte Carlo (MC) based volumetric path tracing (VPT) is adopted as our DVR rendering approach. To guarantee the computational efficiency, MC VPT method is used with limited light samples and can inevitably generate lots of noise, which can greatly reduce user's immersive feeling during MR viewing.

We develop a real-time spatio-temporal denoising algorithm especially for DVR in MR system. The reprojection strategy [3] is resorted to exploiting the temporal coherence between adjacent frames and the spatial coherence between HMD screens. A pixel p of the left or right HMD screen image in t-th frame can find three other corresponding reprojected pixels, i.e. a reprojected pixel on the other HMD screen in t-th frame and two reprojected pixels on the left and right HMD screens in $(t-1)$-th frame. We can set the weight function to calculate the contribution of corresponding reprojected pixels to the pixel value of p. After spatio-temporal denoising, the visual discomfort caused by the noise from MC estimation can be greatly reduced. Finally, the realistic DVR results are transmitted to MR HMD via WiFi for displaying and viewing.

3 Evaluation

3.1 User Study Design

To analyze different experiences offered to users using various rendering methods and lighting effects, and examine the benefit of realistic DVR reflecting dynamic environment illuminations for MR viewing, the user study was conducted in our evaluation. We implemented three DVR methods for MR volume visualization. First, a virtual point light source was used to illuminate the volume data, and the volumetric structures were rendered using Phong shading strategy (*RCP*). The second DVR method was based on VPT without our illumination estimation module (*RTP*). We also placed a virtual point light source at the camera position as *RCP* to illuminate the virtual model. Our realistic DVR method (*RTE*) used the HDR radiance map to provide illumination.

In our user study, 20 participants aged from 20 to 50 years old were invited to our user study. Most of them were engaged in technical occupations with MR development experiences. After inspecting each MR rendering result for three minutes, all participants were asked to evaluate how visually harmonious the integration of volume data with the surrounding real-world environment is. Then, each participant was then asked to rate the experience from 1 to 5 (1 stands for "not harmonious at all" and 5 stands for "identical").

3.2 Result and Discussion

The one-way analysis of variance (ANOVA) was used to demonstrate that the scores of different DVR methods had statistically significant difference ($F(2,72) = 8.985, p = 0.0003$). As shown in Fig. 3, *RCP* is a non-realistic rendering method, corresponding rendering results do not have high-quality material appearance (mean score $\mu = 2.55$, standard deviation score $\sigma = 0.71$). Due to virtual point light sources with limited numbers and fixed positions, the *RTP* method produces


(a) RCP (b) RTP (c) RTE

Figure 3: Visual comparison of MR rendering results between different DVR methods with different illumination settings.

Figure 4: Interactive realistic visualization of medical volume data displayed in our MR prototyping system can respond to the dynamic environment illumination in real time.

the same rendering results in any MR scene. The incorrect shadows might confuse users rather than help them to observe virtual models ($\mu = 2.90$, $\sigma = 0.75$).

In contrast, the proposed method (*RTE*) can generate realistic rendering results that can be integrated into the user's surrounding scene ($\mu = 4.35$, $\sigma = 0.43$). The proposed method obtained immersive and stable results and outperformed other DVR methods in MR. It demonstrates that our method is favored by most involved participants. Furthermore, we also tested different volume data and environment scenes to demonstrate the adaptability of our method. As shown in Fig. 4, the appearance of the rendered volumetric structures is free of uncomfortable noise and artifacts. Besides, the shadowing and shading effects of rendered volumetric structures were consistent with the real objects in real-world scenes.

4 Conclusion

To improve user's immersive feeling during MR viewing, we develop an MR framework for realistic DVR with dynamically varying environment illumination. A preliminary user study proves that the proposed method offers better realisticness and interaction during MR viewing compared to existing DVR solutions. In the future, we would design additional experiments to uncover potential abilities of our framework and facilitate it can be used as a solid foundation for more complicated MR DVR development.

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