Depth Boost: Extended Depth Reconstruction Capability on Volumetric Display

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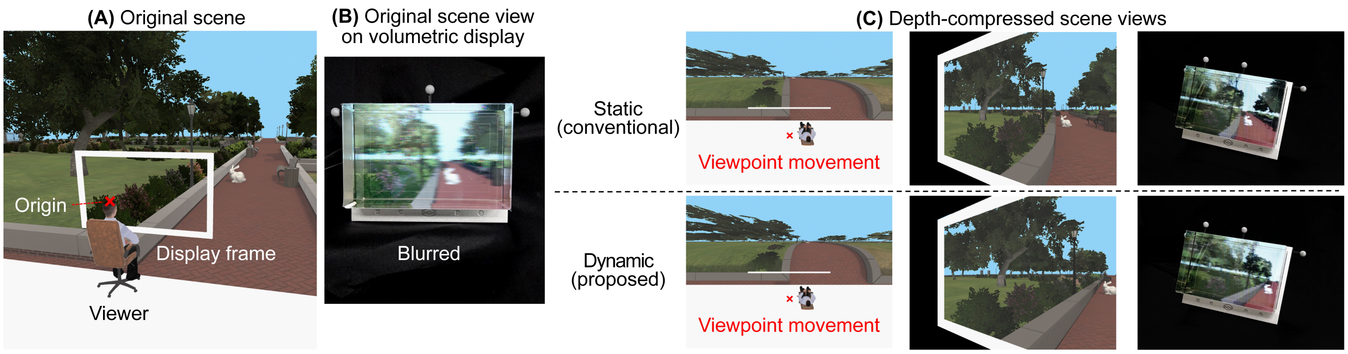

Figure 1: (A) Original scene with assumed viewer and display frame. (B) Original scene view on volumetric display. (C) Comparison between scene views with static and dynamic depth compression. (Left column) Top views of the depth-compressed scenes with viewpoint movement. (Center column) Viewer's observations. (Right column) Depth-compressed scenes shown on volumetric display.

ABSTRACT

A key challenge of volumetric displays is presenting a 3D scene as if naturally existed in the physical space. However, the displayable scenes are limited because current volumetric displays do not have a substantial depth reconstruction capability to show scenes with significant depth. In this talk, we propose a dynamic depth compression method that modifies the 3D geometries of presented scenes while considering changes to the spectator's view point such that entire scenes are fitted within a smaller depth range while maintaining the perceptual quality. Extensive depth compression induces a feeling of unnaturalness in viewers, but the results of an evaluation experiment using a volumetric display simulator indicated that a depth of just 10 cm was needed to show scenes that originally had about 50 m without an unacceptable feeling of unnaturalness. We applied our method to a real volumetric display and validated our findings through an additional user study. The results suggest that our method works well as a virtual extender of a volumetric display's depth reconstruction capability, enabling hundreds of times larger depth reconstruction than that of current volumetric displays.

CCS CONCEPTS

• **Human-centered computing → Visualization**.

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Volumetric displays, Depth compression, Depth extender

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1 PROBLEM SETTINGS

While volumetric displays such as light-field and integral imaging displays can provide glasses-free 3D vision, they have difficulty achieving high quality 3D reconstruction, particularly with objects shown at some distance away from the display surface. The insufficient depth reconstruction capability makes viewers observe significant blur on distant objects (Fig.1 (A) and (B)) [Hoshino et al. 1998; Isaksen et al. 2000]. Physically improving this capability requires the development of flat panel displays with much denser pixels than what is currently possible with the cutting-edge display technology.

Another solution for this problem is modifying 3D scene geometries into a smaller depth range covered by the display's depth reconstruction capability. Since human visual perception is not a piece of measuring equipment but rather an estimator of the visual world from incomplete visual cues, modified shapes are not always perceived as they are. In fact, by using a nonlinear depth compression method, which contracts scene depth depending on object positions in the scene, i.e., the depth of near and distant objects are contracted lightly and heavily, respectively, only one meter is needed to show scenes with hundreds of meters of depth without a feeling of unnaturalness [Sawahata and Morita 2018]. This method shows promise for presenting scenes with almost infinite depth on volumetric displays with limited depth reconstruction capability.

Achieving one meter of depth reconstruction is still challenging for volumetric displays, and this is highly motivating when it comes to improving the depth compression performance. In the conventional methods, unnatural feelings caused by 2D cues, such as shape distortions and unusual object arrangements, and 3D specific perceptual cues, such as puppet theater and cardboard effects, tend to get significant when a viewpoint moves away from the assumed viewpoint (Fig.1 (C), see Sec. 2). Taking the spectator's viewpoint change into account is thus key.

Manipulating scene depth has also been performed in content retargeting [Lang et al. 2010], in which a 3D content designed for a certain environment, e.g., a movie theater, is converted into the optimal disparity condition for another environment, e.g., a television set. However, because the depth of the original 3D content has already been optimized for a viewing environment at the production stage, the degree of depth manipulation in content retargeting is much smaller than that required to show full scale scenes on our target displays. Therefore, any method designed for content retargeting is not enough to solve the problem.

2 APPROACH

We propose a dynamic depth compression method that contracts the scene depth in the same manner as the conventional method but that also considers changes to the spectator's viewpoint. In the conventional method, all scene geometries (vertices) are represented in fixed local coordinates in which the z-axis is perpendicular to the screen center and the origin is located away from the screen on the z-axis, i.e., given v_d as a viewing distance, the screen center was placed at $(0, 0, v_d)$. To contract the scene depth, a point (x, y, z) is nonlinearly mapped to the new position (x', y', z') with $x' = x\,z'/z$, $y' = y\,z'/z$, and $z' = D\,tanh((z - z_f)/D) + z_f$. Note that D is a target depth range and z_f is a depth position of a front plane of it. The monocular retinal image at the origin is not affected by the mapping because x and y are adjusted to maintain the image perspective. However, when the viewpoint moves away from the origin, unnatural cues stemming from the mapping are perceived (Fig.1 (C) upper).

In the proposed method, we measure the viewing position in realtime and update the coordinate-origin frame by frame so that it is always located at the moving viewpoint in contrast to the conventional method, which fixes it regardless of the viewpoint. In our method, no distortion is perceived when viewing the scene with monocular vision at any viewpoint (Fig.1 (C) lower). In reality, the origin is placed at the center of the eyes. Therefore, viewers still have a chance to observe modified visual cues.

3 ACCEPTABLE LEVELS OF COMPRESSION

We empirically estimated how much we can compress scene depth without a feeling of unnaturalness. We used a custom-made volumetric display simulator consisting of a stereoscopic display and a motion tracker. It can present any depth without blur in principle and is suitable for evaluating the unnaturalness of appearances, unlike the current volumetric displays, which cannot present deep scenes without quality degradation. The simulator was designed as a tablet-like device to reproduce a harsher evaluation environment featuring larger viewpoint movements than those typical in a wall-mounted display viewing.

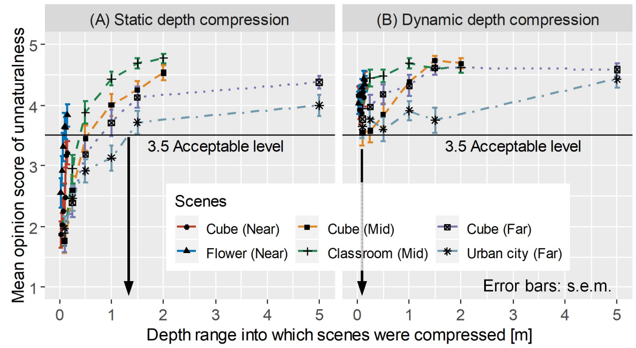

Figure 2: Comparison of reported unnaturalness for scenes with static and dynamic depth compression.

Participants viewed six stimuli consisting of near, middle, and far scenes (two scenes each) with original scene depths of 0.218, 3.05, and 54.5 m, respectively. In each trial, participants compared original and depth-compressed scenes presented 5 secs each sequentially and rated the unnaturalness on a 5-grade impairment scale (5: imperceptible, 4: perceptible, 3: slightly unnatural, 2: unnatural, and 1: very unnatural). We recruited 40 participants with normal or corrected to normal vision. Fig.2 shows the performance comparison between the static (conventional) and dynamic depth compression methods. Stronger depth compression (smaller values on the x-axes) produced worse perceptual quality (more unnatural), but the tendencies of the degradation were different in each method. We found that the static method required a depth of more than 1.3 m in order to provide better naturalness (MOS > 3.5), while the dynamic method required only 10 cm. This result demonstrates that our proposed method can improve the depth compression performance ten times as much as the conventional method.

4 VALIDATION ON A VOLUMETRIC DISPLAY

To validate our findings obtained using the volumetric display simulator, we implemented the dynamic depth compression in a commercially available volumetric display, Looking Glass (Fig. 1 (B) and (C) right). We examined whether our method can virtually extend the depth reconstruction capability to a significantly larger than the original. We asked six participants to choose a scene with more natural depth expression from two presented scenes with the static and dynamic depth compression. They viewed 3D images with motion-tracking-marker-attached plane glasses to track their viewpoints. As the results, five out of six participants reported that the dynamically depth-compressed scenes whose depth was compressed into 10 cm had more natural depth expression, as predicted by the simulator experiment. This demonstrates that the dynamic depth compression method works fine even on real volumetric displays.

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