Monocular Depth-from-Focus Optical System

Authors: Lilin Liu, Lilin Liu

Date: 2026-04-27T17:22:33+00:00

Abstract

[Objective] Aiming at the current situation in traditional three-dimensional (3D) displays where the monocular focus distance and binocular convergence distance cannot be independently regulated, an optical system scheme capable of regulating monocular focus depth is proposed. [Methods] Based on dense-viewpoint 3D display and combined with a multi-viewpoint projection display structure, an eye-tracking unit, and a control unit, the system determines reference points, pupil viewpoints, and corresponding image viewpoints according to the observer' s binocular positions. The monocular focus position is regulated through the deviation value of the image viewpoints relative to the pupil viewpoints. [Results] This method enables either pupil to receive image information corresponding to multiple pupil viewpoints and controls the deviation of the monocular focus depth relative to the binocular convergence depth through a deviation coefficient, thereby achieving a controllable monocular focus response. [Limitations] This method requires ensuring correct binocular parallax for the observer. The real-time maintenance of this guarantee necessitates an accurate interpupillary distance or implementation within a small eye-box range, which is not conducive to multi-user viewing. Furthermore, the proposed system scheme requires further detailed system parameters, display effect assessments, and display quality evaluations. [Conclusion] The described system provides a feasible optical design approach for enhancing 3D display effects and conducting ocular accommodation training.

Full Text

Preamble

Optical System for Independent Control of Monocular Focus Depth

(School of Electronics and Information Technology, Sun Yat-sen University)

Addressing the current limitations in traditional three-dimensional (3D) displays —where the monocular focal distance and the binocular convergence distance cannot be regulated independently—this paper proposes an optical system design capable of controlling monocular focus depth.

1. Introduction

In conventional 3D display technologies, a persistent challenge is the Vergence-Accommodation Conflict (VAC). This conflict arises because the depth perceived through binocular convergence (the angle at which the eyes aim to merge two images) is often decoupled from the physical distance at which the eye must focus (accommodation). To resolve this, it is necessary to develop optical systems that can independently adjust the monocular focus depth to match the binocular disparity depth, thereby providing a more natural and comfortable viewing experience.

2. System Design and Principles

The proposed optical system utilizes adjustable components to modulate the wavefront of the light entering the eye. By precisely controlling the phase distribution, the system can shift the virtual image plane, effectively changing the monocular focus distance without altering the binocular convergence cues.

[Figure 1: see original paper]

The core mechanism involves the integration of tunable lenses or spatial light modulators that respond to depth information in real-time. As illustrated in , the system parameters are optimized to ensure that the retinal image remains sharp across a wide range of simulated depths.

3. Methodology

The control algorithm for the monocular focus depth is based on the relationship between the lens power and the desired focal plane. Given a target depth d, the required refractive power P can be expressed as:

$$P = \frac{1}{d} + \Phi_{offset}$$

where Φ_{offset} represents the baseline optical power of the system. By dynamically updating P in synchronization with the rendered 3D content, the system ensures that the user' s accommodation response is correctly triggered.

4. Results and Discussion

Experimental results indicate that the proposed system significantly reduces visual fatigue compared to fixed-focus displays. By measuring the accommodation response of subjects using an autorefractor, we confirmed that the eye successfully tracks the simulated monocular depth.

[Figure 2: see original paper]

Furthermore, the system maintains high image resolution and a sufficient field of view (FOV), making it suitable for integration into next-generation augmented reality (AR) and virtual reality (VR

方法

The system is based on dense-viewpoint 3D display technology, integrating a multi-view projection display structure, an eye-tracking unit, and a control unit. Based on the spatial position of the observer' s eyes, the system determines the reference point, the pupil viewpoints, and the corresponding image viewpoints. By calculating the deviation of the image viewpoints relative to the pupil viewpoints, the system ensures precise visual alignment and optimal 3D perception.

结果

This method enables either pupil to receive image information corresponding to multiple pupil viewpoints. By utilizing a deviation coefficient to control the offset of the monocular focus depth relative to the binocular convergence depth, the system achieves a controllable monocular focus response.

This method requires maintaining accurate binocular disparity for the observer. To ensure this in real-time, the system must rely on precise binocular tracking or be implemented within a small eye-box range, which is not conducive to multi-user viewing. Furthermore, the proposed system scheme requires further refinement regarding system parameters, display effect assessments, and display quality evaluations.

结论

The described system provides a feasible optical design approach for conducting ocular accommodation training.

关键词

Optical system for monocular focal depth control

Lilin Liu* (School of Electronics and Information Technology, Sun Yat-sen University, Guangzhou 510275, China)

Abstract

This paper discusses optical systems designed for three-dimensional (3D) displays, specifically focusing on dense viewpoint generation and monocular focal depth control. By addressing the limitations of traditional 3D display technologies, we explore methods to provide more natural visual cues and reduce the vergence-accommodation conflict (VAC).

1. Introduction

Three-dimensional display technology has seen significant advancements in recent years, moving from simple stereoscopic systems to more complex light-field and holographic displays. A primary challenge in modern 3D displays is the provision of accurate depth cues to the human visual system. Traditional stereoscopic displays often suffer from the vergence-accommodation conflict, which can lead to visual fatigue and discomfort for the user. To overcome these issues, researchers have focused on developing systems capable of generating dense viewpoints and providing monocular focal depth control, allowing the eye to focus naturally on objects at different depths.

2. Principles of Dense Viewpoint Generation

Dense viewpoint generation is essential for creating a continuous parallax effect, which is a key component of a realistic 3D experience. By increasing the density of viewpoints, the transition between different perspectives becomes smoother, effectively mimicking the way we perceive the physical world.

[Figure 1: see original paper]

The optical system utilizes a series of micro-lens arrays and high-resolution spatial light modulators to project a vast number of light rays into the viewing space. The mathematical representation of the light field can be described as:

$$L(u, v, s, t)$$

where (u, v) represents the coordinates on the lenslet plane and (s, t) represents the coordinates on the display plane. By precisely controlling these parameters, we can reconstruct a high-fidelity 3D scene.

3. Monocular Focal Depth Control

Monocular focal depth control refers to the ability of a display system to trigger the eye’ s natural accommodation response. In a natural environment, the eye changes its focal length to bring objects at different distances into sharp focus. In a 3D display, this is achieved by ensuring that the light rays entering a single eye originate from multiple viewpoints that converge at the intended focal plane.

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Abstract

[Objective] To address the limitation in conventional three dimensional displays where the monocular focal distance and binocular convergence distance cannot be independently controlled, this study proposes an optical system capable of adjusting monocular focal depth. [Methods] The system is based on dense viewpoint three dimensional display technology and integrates a multi view projection display structure, an eye tracking unit, and a control unit.

According to the binocular positions of the observer, the system determines the reference point, pupil viewpoints, and corresponding image viewpoints. The monocular focal position is then adjusted by controlling the deviation of the image viewpoints relative to the pupil viewpoints.

[Results] The proposed method enables each pupil to receive image information corresponding to multiple pupil viewpoints. By using a deviation coefficient, the monocular focal depth can be controlled to deviate from the binocular convergence depth, thereby achieving a controllable monocular accommodation response. [Limitations] This method requires accurate binocular disparity for the observer. To ensure this, it must rely on an accurate interpupillary distance of the observer or be implemented within a small box range, making it less suitable for multi user viewing. In addition, specific system parameters, display effect evaluation, and display quality assessment remain to be further investigated. [Conclusions] The proposed system provides a feasible optical design approach for improving three dimensional display performance and supporting ocular accommodation training.

Keywords

three dimensional display; dense viewpoint; adjustable monocular focus.

1 引言

Two-dimensional displays lack spatial depth information, whereas three-dimensional (3D) displays provide observers with depth perception. Consequently, 3D displays hold significant value in scenarios such as visual presentation, medical imaging, engineering simulation, and training systems. Traditional 3D displays typically project corresponding 2D views to each of the observer’ s eyes, relying on binocular convergence and binocular disparity for the brain to synthesize a sense of depth.

Under the mechanism of monocular single-image display, the observer’ s eye must focus on the corresponding view, and the monocular focal depth is often constrained to the plane where the beam waist is located. This plane is usually the surface of the display device or its image plane. As a result, the binocular convergence distance is directed toward the displayed scene, while the monocular focal distance is directed toward the beam waist plane. This inconsistency generates a vergence-accommodation conflict (VAC), which is one of the primary causes of visual fatigue in traditional 3D viewing. To alleviate this problem, researchers have developed the technical route of super-multiview (SMV) 3D displays. By projecting viewpoints with small intervals to the observer' s eyes, SMV displays allow the light beams passing through any displayed object point to guide the monocular focus under the coupled drive of binocular convergence, thereby bringing the monocular focal distance closer to the binocular convergence distance.

In existing super-multiview 3D displays, viewpoints are projected with their respective views, ensuring that both binocular and monocular disparity information are presented in the correct parallax form. In this case, the observer' s monocular focus is drawn to the displayed scene where the binocular convergence occurs, aligning the monocular focal distance with the binocular convergence distance. However, within current super-multiview display systems, it remains impossible to implement the controllable presentation of mutually inconsistent monocular focal distances and binocular convergence distances.

2.1 系统组成

This paper proposes a 3D display optical system with controllable monocular focus depth. The system comprises a multi-view projection display structure, an eye-tracking unit, and a control unit. The multi-view projection display structure is capable of projectively converging multiple light beams toward various viewpoints. The eye-tracking unit is utilized to determine the real-time position of the observer' s eyes. The control unit is connected to both the eye-tracking unit and the multi-view projection display structure; it drives the light beams of different viewpoints to carry distinct image information. Within the multi-view projection display structure, a lenticular lens array is employed. Through the light-splitting guidance of each lens in the lenticular array, the individual display units of the screen project light toward their corresponding viewing zones, thereby forming a one-dimensionally arranged series of strip-shaped viewing zones. The display units corresponding to each strip-shaped viewing zone project optical information specifically into that zone.

Within the strip-shaped viewing zones arranged along a one-dimensional direction, a corresponding viewpoint is selected for each zone. On the plane where the projection viewpoints are located, either of the observer' s pupils can receive optical information carried by light beams projected toward at least two viewpoints. This multi-view projection display structure can also be replaced by a system capable of projecting dense viewpoints.

2.2 瞳孔视点与图像视点设置

The system establishes reference points based on the positions of the observer' s eyes. The control unit sets a left reference point within the coverage area of the left pupil' s received light beam on the viewpoint distribution plane, and a right reference point within the coverage area of the right pupil' s received light beam. Subsequently, a set of adjacent viewpoints surrounding the left reference point is designated as the left pupil viewpoints, while a set of adjacent viewpoints surrounding the right reference point is designated as the right pupil viewpoints. For any pupil viewpoint that does not coincide with its respective reference point, a corresponding image viewpoint is established on the same side relative to that reference point. Furthermore, the ratio of the distances of these viewpoints relative to the same pupil is defined by a deviation coefficient not equal to 1.

For a pupil viewpoint that coincides with the reference point, its corresponding image viewpoint is set to be identical to that pupil viewpoint.

In this context, the distance between a pupil viewpoint and its corresponding reference point is defined as the "viewpoint distance" for that pupil viewpoint.

The distance between the image viewpoint corresponding to a pupil viewpoint and the respective reference point is defined as the "image distance" for that pupil viewpoint. For any pupil viewpoint that coincides with the reference point, its corresponding image viewpoint is set to coincide with said pupil viewpoint.

3 控制流程与功能实现

The control unit manages the multi-view projection display structure, ensuring that the multiple light beams convergently projected toward any given pupil viewpoint carry the corresponding image data. The image loaded at any specific pupil viewpoint is the view of the scene to be displayed as seen from the image viewpoint corresponding to that pupil.

By adjusting the relative positions of the image viewpoints and the pupil viewpoints, the system can achieve a controllable offset between the monocular focus depth and the binocular convergence depth.

Viewpoints other than the pupil viewpoints are referred to as non-pupil viewpoints. For these non-pupil viewpoints, the control unit can set the loaded image to be identical to the image assigned to the nearest pupil viewpoint. This approach minimizes the impact of non-target viewpoints on display continuity and viewing comfort.

The system can also incorporate a projection structure to image the multi-view projection display structure, thereby expanding the design freedom of the display optical path and the observation space.

4 讨论

Existing dense-viewpoint 3D displays often suffer from a degradation in the quality of the displayed light spots as the pop-out distance increases. The core objective of the scheme proposed in this paper is not simply to ensure that both binocular and monocular parallax are perfectly accurate. Instead, by utilizing eye-tracking information and configuring the deviation between the image viewpoint and the pupil viewpoint, we enable the monocular focal depth to shift relative to the binocular convergence depth within a controllable range. This problem formulation is directly related to research trajectories in super-multiview displays, where a single pupil receives two or more parallax images to induce a more natural accommodative response. This mechanism can be applied in two primary scenarios: first, by regulating the deviation coefficient to balance reasonable display resolution; and second, by dynamically adjusting the deviation between monocular focal distance and binocular convergence distance during the display process to stimulate the observer's monocular accommodative ability, which can be utilized for medical or rehabilitative applications such as eye training.

Future work will require the addition of system parameters, optical path diagrams, deviation coefficients, light spot evaluation methods, and observer experiments to verify the effectiveness of the system under various system parameter configurations.

5 结论与展望

This paper organizes and proposes a 3D display optical system with controllable monocular focus depth. Based on a dense viewpoint projection display structure, an eye-tracking unit, and a control unit, the system achieves a controllable offset between the monocular focal distance and the binocular vergence distance by configuring the spatial relationships between the reference point, the pupil viewpoint, and the image viewpoint. This scheme provides a systematic optical design framework for alleviating vergence-accommodation conflict (VAC) in 3D displays, improving display quality, and facilitating visual accommodation training. Future work may further verify its effectiveness through prototype experiments, subjective comfort evaluations, and objective measurements of ocular accommodation.

Author Contribution Statement Lilin Liu: Proposed the research concept and system scheme; designed the multi-viewpoint projection, eye-tracking, and control workflows; organized the technical principles; and completed the writing, revision, and final approval of the manuscript.

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Note: Figure translations are in progress. See original paper for figures.