Postprint of the Application of Binocular Stereoscopic Display Technology in 3D Visualization of Lunar Surface Topography

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Abstract

Based on terrain and image data acquired by the Chang' e-2 probe, binocular stereo display technology was applied to three-dimensional visualization of lunar surface morphology to construct a lunar three-dimensional stereo visualization system. The principle of binocular stereo display is introduced, and the specific implementation of the lunar three-dimensional stereo visualization system is described in detail. First, the system design scheme and hardware environment are discussed; subsequently, the organization methods for massive lunar terrain data and real-time rendering approaches are addressed; finally, employing an off-axis model binocular stereo display method, comfortable stereo effects are achieved. Applications in lunar science popularization and scientific research demonstrate that the system possesses good practical value.

Full Text

Application of Binocular Stereo Display Technology in Three-Dimensional Visualization of Lunar Surface Morphology

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Abstract: Based on lunar terrain and image data obtained from the Chang' e-2 probe, this study applies binocular stereo display technology to three-dimensional visualization of lunar surface morphology and constructs a lunar three-dimensional stereo visualization system. The paper introduces the principles of binocular stereo display and elaborates on the specific implementation of the lunar stereo visualization system. First, the system design framework and hardware environment are discussed; next, the organization method for massive lunar terrain data and real-time rendering techniques are presented; finally, an off-axis model-based binocular stereo display method is adopted to achieve comfortable stereo effects. Applications in lunar science popularization and research demonstrate that the system possesses significant practical value.

Keywords: Chang’ e-2; binocular stereo display; lunar three-dimensional visualization

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1. Introduction

Since the successful launch of China’ s first lunar orbiter Chang’ e-1 in 2007, China has successfully conducted three lunar exploration missions, acquiring vast amounts of precious lunar image data. During its year-long orbital mission, Chang’ e-1 utilized its three-line array camera to obtain full lunar images at 120 m resolution, which were meticulously processed by the ground application system to generate a global lunar digital elevation model (DEM) at 120 m spatial resolution. During its half-year orbital mission, Chang’ e-2 employed its two-line array camera to acquire full lunar image data at 7 m resolution and high-resolution images of the Sinus Iridum region at 1.5 m resolution. Through careful processing by the ground application system, these data yielded a global lunar DEM with spatial resolution reaching 50 m. Chang’ e-3 delivered China’ s first lander and Yutu rover to the lunar surface in 2013, initiating in-situ and roving exploration activities. The Yutu rover’ s panoramic camera has acquired substantial amounts of lunar data around the landing site.

These three successful lunar exploration missions have not only provided China with independent lunar exploration data but also compensated for the shortcomings of unclear and incomplete lunar image data obtained abroad, offering excellent data resources for people to understand the true and comprehensive morphology of the Moon. Based on clear and comprehensive Chang’ e probe image data and high-resolution DEM data, three-dimensional visualization of lunar morphology can facilitate more in-depth quantitative and qualitative analysis of the Moon, help people understand the Moon in an intuitive and convenient manner, and hold significant importance for China to better conduct lunar exploration activities. Domestic scholars have conducted extensive research on lunar morphology visualization based on Chang’ e data, including creating three-dimensional lunar morphology maps based on Chang’ e-1 terrain data, developing lunar three-dimensional visualization systems based on Chang’ e-1 CCD camera and laser altimeter data, and constructing Chang’ e-2 on-orbit operation visual simulation systems based on Chang’ e-2 terrain and image data. Xing et al. discussed key technologies for WebGIS-based lunar visualization.

However, almost all previous visualization research has employed two-dimensional planar display methods, which have inherent limitations. The real world is three-dimensional, and with the development of computer technology, three-dimensional stereo visualization technology based on binocular stereo display has advanced rapidly. Compared with traditional two-dimensional display technology, binocular stereo display technology enables human eyes to obtain stereo vision from a two-dimensional display plane, reproducing objective scenes in a form more consistent with human visual habits and providing viewers with an immersive experience. Binocular stereo display technology offers greater information capacity, stronger impact, and enhanced realism and interactivity [5]. As a key technology in virtual reality and visualization, binocular stereo display has broad applications in fields such as movies and television [6-12].

2. Principles of Binocular Stereo Display

2.1 Parallax When observing the real three-dimensional world, the two eyes see a pair of images with certain disparities projected onto the retinas due to the interpupillary distance. The brain integrates these disparity image pairs through eye movement adjustment to obtain distance perception of objects. The principle of binocular stereo vision simulates this process. Based on the relative position of the human eyes to the screen, computers simulate and generate disparity images seen by the left and right eyes at that position. Specialized binocular stereo display hardware ensures that the left eye only sees the simulated left image and the right eye only sees the simulated right image, forming stereo vision in the brain.

The key factors in forming binocular stereo vision are parallax and the stereo display hardware foundation. Parallax refers to the horizontal distance between corresponding points of left and right disparity images displayed on the screen, which determines the stereo perception of images in the brain. By adjusting the parallax size of left and right disparity images, different stereo perceptions can be created. Based on different stereo sensations formed in the brain, parallax can be divided into positive parallax, negative parallax, and divergent parallax.

When the distance between two corresponding points in the disparity images is less than the interpupillary distance and the sight lines of both eyes do not cross in front of the screen, positive parallax is generated. The brain fuses these two corresponding points to produce a three-dimensional point that appears to be located behind the screen plane (Figure 1(a)). When two corresponding points with zero parallax overlap on a two-dimensional display, this point appears on the two-dimensional screen plane when viewed with both eyes (Figure 1(b)). When the distance between two corresponding points in the left and right disparity images is less than the interpupillary distance and the sight lines of both eyes cross in front of the screen, negative parallax is generated. The brain fuses these two corresponding points to produce a three-dimensional point that appears to float between the screen and the viewer (Figure 1(c)). When the distance between two corresponding points is greater than or equal to the interpupillary distance, the brain cannot focus on these two points, resulting in ghosting and causing fatigue and discomfort. In this case, the brain instinctively attempts to focus continuously, even for a short period (Figure 1(d)).

2.2 Binocular Stereo Display Hardware Binocular stereo display hardware refers to auxiliary devices that employ optical and other technical means to ensure that the left and right eyes can only see the corresponding left and right disparity images on the screen. Based on the implementation principles of stereo hardware, the technologies can be categorized into several types, including spatial division technology and time-division technology.

3. Design of the Lunar Stereo Visualization System

3.1 System Framework Based on the principles of binocular stereo display and computer graphics knowledge, this paper designs and constructs a lunar three-dimensional stereo visualization system. The system construction process is illustrated in Figure 3. This study utilizes Chang' e-2 7 m resolution orthoimage data and 50 m resolution DEM data to build a real-time interactive lunar morphology stereo visualization system. The construction process involves: first preprocessing lunar data to generate global terrain model data; then incorporating the terrain model data into the lunar stereo visualization system; dynamically loading terrain data blocks based on viewpoint position; completing stereo rendering using an off-axis model based on binocular viewpoints; and finally outputting the rendered left and right disparity image signals to a four-channel stereo projection system for stereo projection display.

3.2 Hardware Environment for the Lunar Stereo Visualization System The lunar stereo visualization system employs an immersive four-channel stereo projection system as its display platform. The hardware configuration includes: a graphics workstation, four Barco projectors supporting active stereo display with seamless fusion, a 120 Hz stereo signal transmitter, a signal synchronization matrix, and several shutter glasses. This hardware system uses a 120 Hz refresh rate for stereo projection display. The Quadro Plex system alternately outputs left and right stereo video signals in real-time rendering. The synchronization matrix synchronizes the four-channel video signals and outputs them to four seamlessly spliced stereo projectors. Simultaneously, the stereo signal transmitter emits stereo synchronization signals to the shutter glasses, ensuring that the viewer' s left eye only sees the left image and the right eye only sees the right image, thereby forming stereo vision.

3.3 Terrain Data Organization and Rendering The Chang' e-2 DEM and digital orthophoto map (DOM) data cannot be loaded into computer memory all at once. To achieve real-time interactive roaming of the entire Moon, the data must be effectively organized and dynamically scheduled. This paper preprocesses the DEM and DOM data to construct terrain model blocks and organizes these terrain blocks using a quadtree structure. The specific data organization method is shown in Figure 5: global data is first divided into eastern and western hemispheres, then each hemisphere is recursively quartered along meridians and parallels, and organized in a quadtree structure. Each quadtree node holds a terrain unit, which consists of a 256$×$256 pixel image block and a corresponding terrain block with matching geographic location.

This paper employs a Level of Detail (LOD) model rendering algorithm to dynamically schedule terrain units for rendering. The LOD rendering algorithm means that during model rendering in a scene, areas farther from the viewpoint have lower resolution while areas closer to the viewpoint have higher resolution. As the viewpoint changes, the scene changes continuously, ensuring smooth display of large-scale data without affecting visual quality [13].

3.4 Binocular Viewpoint Model Selection and Stereo Display Implementation 3.4.1 Selection of Binocular Viewpoint Model

After completing the virtual lunar model, an appropriate binocular viewpoint model must be selected to render the stereo scene for achieving good lunar stereo roaming effects. In virtual scenes, according to the binocular disparity principle, left and right viewpoints with horizontal separation and convergence are set, and the virtual scene seen by each viewpoint is projected onto a two-dimensional screen for stereo display. The binocular viewpoint model constructed using this method is called the toe-in model (Figure 6(a)). Its significant drawback is the introduction of vertical parallax and distortion of horizontal depth planes [14].

The off-axis model is an improvement over the toe-in model. While maintaining parallel sight lines for left and right viewpoints, the off-axis model shifts the projected images in opposite horizontal directions after viewpoint projection to form stereo disparity images. By setting two asymmetric view frustums (the shaded portions in Figure 6(b) represent asymmetric view frustums), the off-axis model ensures parallel sight lines while avoiding vertical parallax and solving depth plane distortion problems.

3.4.2 Implementation of Three-Dimensional Stereo Visualization

Three-dimensional effects in computer virtual worlds are achieved by transforming three-dimensional coordinates of the virtual scene through viewpoint transformation and then through perspective projection onto a two-dimensional plane. To implement three-dimensional stereo visualization, left and right viewpoints with horizontal offset from the original viewpoint must first be constructed based on the off-axis model principle. Simultaneously, shear matrices are multiplied by the original perspective projection matrices to perform shear transformations on them. The three-dimensional coordinates of the virtual world are then multiplied by the inverse matrices of the transformed left and right viewpoint matrices, and subsequently multiplied by the sheared left and right viewpoint projection matrices to project the virtual three-dimensional world into stereo images with left-right disparity. Finally, the resulting left and right disparity images are alternately displayed.

The translation and shear transformation processes of the transformation matrices and projection matrices are as follows:

$$\begin{aligned}
\textbf{LeftViewMatrix} &= \textbf{LeftTranslationMatrix} \times \textbf{ViewMatrix} \\
\textbf{LeftProjectionMatrix} &= \textbf{LeftShearMatrix} \times \textbf{ProjectionMatrix} \\
\textbf{RightViewMatrix} &= \textbf{RightTranslationMatrix} \times \textbf{ViewMatrix} \\
\textbf{RightProjectionMatrix} &= \textbf{RightShearMatrix} \times \textbf{ProjectionMatrix}
\end{aligned}$$

In the above matrices, **LeftViewMatrix** and **RightViewMatrix** are the transformed left and right viewpoint transformation matrices; **LeftTranslationMatrix** and **RightTranslationMatrix** are the translation matrices that shift the viewpoint left and right; **ViewMatrix** is the original viewpoint transformation matrix; **LeftProjectionMatrix** and **RightProjectionMatrix** are the transformed left and right viewpoint projection matrices; **LeftShearMatrix** and **RightShearMatrix** are the shear transformation matrices corresponding to the left and right viewpoints that shear the original perspective projection; and **ProjectionMatrix** is the original perspective projection matrix.

The two translation matrices **LeftTranslateMatrix** and **RightTranslateMatrix** are respectively:

$$\textbf{LeftTranslateMatrix} = \begin{pmatrix} 1 & 0 & 0 & -\frac{IPD}{2} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \quad \textbf{RightTranslateMatrix} = \begin{pmatrix} 1 & 0 & 0 & \frac{IPD}{2} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

The two shear matrices **LeftShearMatrix** and **RightShearMatrix** are respectively:

$$\textbf{LeftShearMatrix} = \begin{pmatrix} 1 & 0 & \frac{IPD}{2\times\text{ConvergenceDistance}} & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \quad \textbf{RightShearMatrix} = \begin{pmatrix} 1 & 0 & -\frac{IPD}{2\times\text{ConvergenceDist}} \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{pmatrix}$$

where IPD (Interpupillary Distance) is the binocular disparity. Appropriate binocular disparity is jointly influenced by factors such as the viewpoint’ s field of view, display screen size, and viewing distance [15].

During rendering, the lunar stereo visualization system employs quad-buffer rendering technology: rendering the left viewpoint view to the left back buffer and the right viewpoint view to the right back buffer. The left and right viewpoint images are rendered alternately. To avoid flickering, the left back buffer is swapped to the left front buffer and the right back buffer to the right front buffer to complete the alternating display of left and right rendered images. The stereo moon effect rendered based on the off-axis model is shown in Figure 7, with the binocular disparity set to 0.006 (interpupillary distance of 0.06 m).

4. Applications and Conclusion

This paper applies binocular stereo display technology to full lunar morphology visualization research. Based on Chang'e-2 DEM and DOM data, combined with a four-channel stereo projection system, an immersive lunar three-dimensional stereo visualization system has been implemented. The off-axis model-based binocular stereo display method provides better immersion and effectively assists people in understanding lunar morphological features more intuitively. The system, equipped with a 1:1 scale rover model and projection ground screen system, has been used to construct an immersive virtual lunar surface exploration scene (Figure 8). It has received numerous visits from primary and secondary school students, playing an important role in popularizing lunar science and publicizing the Chang' e program achievements.

With the deepening and further development of China' s deep space exploration, binocular stereo display technology will undoubtedly be more widely applied in the three-dimensional visualization of deep space exploration data.

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