Research on Multi-Projection Stitching Technology for Digital Planetarium Domes (Postprint)

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Abstract

Traditional optical planetariums are gradually being superseded by powerful digital planetariums due to inherent drawbacks such as challenging program production, high costs, and limited functional expandability. As astronomy education and science popularization continue to advance, domestic demand for digital planetariums is growing substantially. The core technology of digital planetariums is dome projection. To address certain technical challenges in dome projection technology, such as low automation levels and the requirement for manual intervention, a multi-projector automatic alignment scheme that is readily implementable for small and medium-sized dome planetariums is proposed. The scheme' s core functionalities—including geometric correction, brightness correction, and color correction—are elaborated in detail. The proposed scheme offers operational convenience and ease of implementation, exhibits excellent performance for small and medium-sized domes, and provides valuable reference for large-scale dome applications.

Full Text

Research on Multi-Projector Stitching Technology for Dome Digital Planetariums

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Abstract

Traditional optical planetariums are gradually being replaced by powerful digital planetariums due to their high program production costs, technical complexity, and limited extensibility. With the growing promotion of astronomy education and science popularization in China, the demand for digital planetariums has increased significantly. The core technology of digital planetariums is dome projection. To address technical challenges in dome projection, such as low automation levels and the need for manual intervention, this paper proposes an easily implementable automatic multi-projector stitching solution for small and medium-sized dome planetariums. The core functions of this solution—including geometric correction, brightness correction, and color correction—are discussed in detail. This approach is convenient to operate, easy to implement, performs well for small and medium-sized domes, and offers valuable insights for large-scale dome applications.

Keywords: Digital planetariums; Dome projection technology; Geometric correction; Brightness correction; Color correction; Automatic calibration

1. Development of Planetarium Display Technology

The world' s first optical planetarium projector was born in Germany in 1923, and for decades thereafter, optical planetariums dominated the field. With the emergence and rapid development of digital video technology, digital cinemas entered commercial operation, and digital video technology also began playing an increasingly important role in astronomy science venues. In 1983, the American company Evans & Sutherland (E&S) launched the Digistar digital planetarium system, marking the formal entry of digital video technology into planetariums and signaling a trend toward replacing film projectors, thus ushering in the era of digital planetariums.

Traditional planetariums primarily used various optical planetarium projectors to simulate starry skies, demonstrating celestial phenomena such as the rising and setting of the sun and the orbital motion of planets as seen from different locations on Earth. However, traditional optical planetariums had limitations, including relatively limited content, complex mechanical components, and cumbersome long-term upgrade and maintenance procedures. Digital planetariums can not only demonstrate starry skies like optical planetariums but also play high-resolution dome videos, using the immersive stereoscopic experience of video and dome to bring audiences various astronomical spectacles, thereby significantly enhancing the educational function of planetariums.

The projection display technology used in digital planetarium systems is called dome projection technology, which involves using one or more projectors to project complete, continuous images onto a spherical screen. Dome projection can achieve high-resolution, wide-angle display effects, providing a novel visual experience. The number of projectors is determined by the dome diameter. Generally, for smaller domes, a single projector with a fisheye lens can complete the display, while larger domes require multiple projectors with stitching display methods. There is no strict boundary for dome diameter size and projection method, but most large planetariums and dome theaters in China adopt multi-projector stitching display methods.

In 2007, after two years of renovation, the old Beijing Planetarium reopened. The planetarium hall was equipped with a German Zeiss optical planetarium projector and, at the time, the world' s highest-resolution all-sky digital projection system. This system used seven digital projectors for image stitching, with eight high-performance graphics computers processing tasks in parallel. The real-time computed digital starry sky images could cover the entire dome, forming an overall resolution of 7800 × 7800, perfectly complementing the optical planetarium projector and providing audiences with a more realistic visual experience closer to natural conditions in the wilderness.

In 2010, China' s first interactive digital planetarium based on the WorldWide Telescope (WWT) was established at Beijing Normal University. WWT is a purely digital interactive planetarium software and scientific data visualization platform that integrates observation data from major astronomical telescopes worldwide, including the Hubble Space Telescope and the Sloan Digital Sky Survey, presenting them through innovative data visualization methods to display the real universe three-dimensionally to audiences. This planetarium can both conduct astronomical demonstrations using WWT software and play dome videos, representing a powerful and conceptually advanced digital planetarium.

For WWT interactive planetariums and other digital planetariums using multiple projectors, the key to dome projection technology is obtaining complete images covering the entire dome through multi-projector image stitching. However, many current multi-projector dome display technologies have cumbersome construction processes and low automation levels. If projectors are moved by external environmental influences during use, complex recalibration is required. To address these issues, this paper proposes an automatic calibration technology for dome projection based on fisheye cameras, targeting small and medium-sized dome planetariums. Through automatic geometric, brightness, and color correction, this technology obtains large-screen output images with uniform brightness and color. The following sections detail the core steps of this technology and present specific implementation and verification.

2. Key Technologies for Digital Planetarium Projection Stitching

The key technologies for digital planetarium projection display are geometric correction, brightness correction, and color correction. Geometric correction primarily solves the problem of maintaining spherical straight lines when images are displayed on the dome. For example, if a continuous straight line needs to span multiple projectors, the stitching across these projectors must ensure the line remains a spherical straight line on the dome. Brightness correction mainly addresses brightness continuity after stitching, ensuring consistent brightness across all regions of the dome. Color correction primarily solves color continuity after stitching, ensuring consistent color output from different projectors on the dome.

2.1 Geometric Correction Principle

Geometric correction mainly includes image distortion correction for individual projector images and alignment correction between multiple projector images. Geometric correction achieves changes in output image orientation and size through geometric transformations, enabling multiple projectors to output a complete image together. Since the dome is a curved surface, different positions on the dome produce varying degrees of distortion. Simultaneously, to achieve seamless stitching, adjacent projectors must overlap certain regions. When projectors project onto the dome, edge images are severely stretched, necessitating geometric correction of projector output images.

Many researchers have studied geometric correction for planar multi-projector displays, proposing methods using a single camera to achieve multi-projector geometric correction by establishing correspondence between camera space and display space. These methods, called parametric approaches, extract several sets of feature points through projection and photography to calculate correspondence matrices, thereby obtaining the relationship between projector coordinate systems and screen coordinate systems. Parametric methods are suitable for planar projection correction with few feature point sets, as planar projection images have no distortion. However, for spherical projection screens, it is difficult to obtain projector position information through parametric calculation methods, requiring as many feature points as possible to accurately characterize distortion information.

To address the shortcomings of parametric methods and the characteristics of dome screens, this paper proposes a non-parametric method using fisheye lens cameras for geometric correction. This method does not require solving correspondence matrices, avoiding complex calculations with multiple feature points. The core of the non-parametric method involves the projector projecting feature points according to a specific encoding pattern, where feature points consist of clusters of pixels with high density to characterize projector image distortion and position information. A camera photographs the feature point images, and through the encoding pattern, correlates the feature points in the photo with those projected by the projector one-to-one. By analyzing the coordinate positions of feature points in the photo, the projector' s position and distortion information across the entire screen is obtained. The range of feature points in the photo represents the projector' s relative projection range, while relative positional changes between feature points represent projector image distortion information.

After obtaining the correspondence and coordinates of feature points in both coordinate systems, texture mapping methods can be used to texture-map the output image onto the projector space based on feature point coordinate information, achieving geometric correction. This paper reduces feature point size to the pixel level, treating each projector pixel as a feature point to maximize feature point density. Designing a reasonable pixel encoding algorithm that enables each projector pixel to be located in the photo becomes key to the non-parametric method.

Each projector pixel can be uniquely identified by its horizontal and vertical coordinate values. This paper proposes encoding the binary coordinate values of each pixel separately to form regularly displayed encoding images. Each pixel uniquely corresponds to a binary coordinate value. After photographing with a camera, the projector' s display area in the photo will show this regular encoding pattern, meaning certain pixels in the photo also conform to this encoding pattern. Through the encoding pattern, the coordinates of these photo pixels in the projector coordinate system can be calculated, establishing correspondence between camera coordinate pixels and projector coordinate system pixels.

Due to resolution differences between the projector and the photo, some projector coordinate system pixels may not find corresponding pixels in the camera coordinate system. In such cases, interpolation is performed based on the coordinate values of adjacent pixels in the camera coordinate system to obtain the corresponding coordinates. The coordinate values of corresponding pixels in both coordinate systems form the data foundation for texture mapping.

The specific principles and steps are as follows:

Step 1: Obtain pixel encoding images. For a projector with resolution 1280×800, the horizontal coordinate value binary number s is 1010000000 (10 bits), and the vertical coordinate value binary number t is 1100100000 (10 bits). For each bit b of s (0-10), create a grayscale image of size 1280×800. If $b = 1$, pixel A in the corresponding image displays pure white (brightness = 255); if $b = 0$, pixel A displays pure black (brightness = 0). After displaying all bit-corresponding images, display the inverse images of the above images in sequence. That is, if $b = 1$, the pixel displays pure black; if $b = 0$, it displays pure white. The two images with the same display order are considered a group. The projector' s output image becomes a series of black-and-white vertical striped images. The same process is applied to the vertical coordinate binary value t to generate 0-10 horizontal stripe images. Each image projected onto the dome is photographed with a fisheye camera and denoised for use in the next step of establishing pixel correspondence between the two coordinate systems.

Step 2: Establish correspondence from camera coordinate system pixels to projector coordinate system pixels. The correspondence R from camera coordinate system pixels to projector coordinate system pixels is decomposed into horizontal coordinate S correspondence Rs and vertical coordinate T correspondence Rt, calculated separately. Rs and Rt each represent a binary number, with R representing the coordinate composed of Rs and Rt. In the above steps, 0-10 groups of images are used to calculate the 10-bit binary number of S. To calculate Rs, first set all bits of Rs to 0. For the nth group of images (n = 0-10), subtract the brightness values of corresponding pixels between the two inverse images. Let Ω represent the brightness difference of corresponding pixels in the two images. Set a reasonable threshold for Ω. If Ω < - , then the nth bit of Rs is 1; if Ω > , the nth bit is 0; for other Ω values, the pixel is not within the projector' s display range. The same process is applied to other image groups to obtain the 10-bit binary number Rs. Similarly, Rt can be calculated. After traversing all pixels in the camera coordinate system and taking only pixels within the projector' s display area in the photo, if a pixel' s calculated Rs and Rt values correspond to a binary coordinate value in the projector coordinate system, a correspondence is established between the two pixels.

Step 3: Obtain correspondence from projector coordinate system pixels to camera coordinate system pixels. Due to significant differences between projector pixel resolution and photo pixel coverage, a projector with resolution 1280 × 800 may only occupy 600 × 400 pixels in the photo. While these 600 × 400 pixels can find corresponding pixels in the projector, other projector coordinate system pixels have no real corresponding pixels in the camera coordinate system. This paper uses bilinear interpolation based on known adjacent pixel correspondences to calculate coordinates for these pixels, obtaining R^{-1} containing all projector pixels.

Step 4: Texture mapping. Texture mapping is the process of mapping texture pixels in texture space to pixels in screen space. After establishing correspondence between all projector space pixels and camera space pixels, the output image can be used as a texture and mapped to projector space through OpenGL texture mapping, enabling each projector to output a complete image. During texture mapping, specifying projector pixel coordinates and corresponding texture coordinates is crucial. Texture coordinates are calculated based on the coordinates of corresponding pixels in the camera coordinate system, achieving geometric correction of the projector.

2.2 Brightness Correction Principle

After geometric correction, brightness in overlapping areas between two projectors appears significantly higher than other regions, forming bright bands. Images in these bright bands are displayed twice, making their brightness double that of other areas, which severely affects visual effects. Brightness correction is needed to achieve uniform brightness across the entire image.

This paper uses alpha channel mask image blending to attenuate brightness in overlapping regions. Alpha is used to measure pixel or image transparency, representing an additional color component beyond RGB. In uncompressed OpenGL, Alpha = 255 means the pixel is completely opaque, while Alpha = 0 means completely transparent. By generating an alpha mask image for each projector, where each pixel' s alpha value is calculated based on its position, the alpha value increases in overlapping areas. Multiplying the mask image with the output image during projection attenuates overlapping region brightness, while non-overlapping areas maintain alpha = 1, preserving normal brightness.

Using two-projector overlap as an example, the overlap region is normalized to [0,1], with 0 representing the overlap start and 1 representing the end. The alpha weighting function for the upper projector image is:

$$F(x) = \begin{cases} 0.5(2x)^p, & 0 \leq x \leq 0.5 \\ 0.5[2(1-x)]^p, & 0.5 \leq x \leq 1 \end{cases}$$

where x is the pixel' s distance to the overlap edge, and p controls the function F' s curve, affecting brightness variation and correction results. Multiplying the output image with the mask image yields the final alpha value for each pixel in the mask image.

2.3 Color Correction Principle

Projectors used for stitching may have inconsistent color spaces. Careful observation reveals color differences between different projectors' images, affecting visual effects and necessitating pre-calibration. Color correction primarily aims to minimize differences between different projector color spaces.

Hardware-based color correction methods include colorimeter-based color matching and spectroradiometer-based correction, but these devices are expensive and difficult to automate. This paper proposes a nonlinear optimization method for projector color models. Let the standard color space be M and the ith projector' s color coordinate space be Mi = [Ri, Gi, Bi]. The transformation relationship between the ith projector and the standard color space is Mi = Hi • Mp, where Hi is a 3$×$3 matrix mapping projector colors to standard colors.

In color correction, standard projection colors are defined within a standard color gamut. Each projector projects a standard color template, and after projection, n groups of corresponding color values are obtained. The goal is to find Hi that minimizes ‖Mi - HMpi‖. Through nonlinear optimization methods, the transformation matrix H^{-1} required for color correction is obtained.

3. Implementation of Dome Projection Stitching Correction System

3.1 System Development and Operation Environment

The system uses Ubuntu as the development platform and C++ as the programming language, with texture mapping implemented using OpenGL library functions. The process begins by selecting an appropriate digital camera and fisheye lens. A mainstream resolution digital camera is chosen, and based on dome size, the camera height and focal length are adjusted to cover the dome with clear images. Proper matching of digital cameras and lenses is essential.

The system connects the control computer and display sub-computers via network. Projectors are fixed at the dome edge, with positions adjusted so that projection areas partially overlap on the dome. The camera connects to the control computer, while each sub-computer connects to its projector. Before the calibration process, indoor visible light sources must be blocked to avoid affecting photo quality, as photo quality directly impacts the calculation of coordinate system correspondence R during geometric correction. During calibration, camera and projector positions must remain fixed.

Using two projectors as an example, the control computer is configured with projector count and resolution. Each projector sequentially displays encoding images, which the control computer captures with the camera, denoises, and stores. After setting reasonable thresholds, the system calculates correspondence R and R^{-1}, performs pre-correction on output images, and outputs corrected images to the dome, producing seamless stitched images.

[Figure 4: see original paper] shows the deployment diagram of the camera and two projectors. Based on projector positional relationships obtained during geometric correction, the overlap region between projectors is determined and normalized. Alpha mask images are calculated for each projector and blended with corresponding projector images to attenuate overlapping region brightness, achieving uniform brightness across the dome.

A color checkerboard is created using common colors and projected by each projector. Using coordinate system correspondence from geometric correction, color values of corresponding color squares from different projectors are obtained. The color correction transformation matrix H^{-1} for each projector is calculated through nonlinear optimization methods. Color correction is executed in real-time during image display, applied at the moment images are distributed to projectors.

[FIGURE:5(a)] shows output from two projectors before geometric correction, where misalignment is evident. This phenomenon is corrected through geometric correction in [FIGURE:5(b)]. [FIGURE:5(c)] shows the bright band between projectors, which is eliminated in [FIGURE:5(d)] after brightness correction. [FIGURE:5(e)] shows the image after color correction. It should be noted that since mainstream projectors have relatively small color space differences and photographing displayed images introduces variations, the difference between images before and after color correction is not obvious in the figures.

After completing all correction steps, images or videos are loaded, and through synchronized output from each projector, seamless, uniformly colored, and evenly bright images are obtained on the dome. To ensure real-time synchronization, identical equipment models should be used for all host computers and projectors, and video playback software must guarantee synchronized frame output across all projector channels.

4. Summary and Outlook

This paper presents the design and implementation of an automatic multi-projector stitching technology for small and medium-sized dome planetariums, addressing key issues including geometric correction, brightness correction for overlapping regions, and color correction between projectors. The method is feasible for constructing multi-projector display systems for dome screens and has achieved good results. The system is convenient to configure and easy to implement, making it suitable for integration into WWT interactive digital planetarium systems to promote the development of astronomy education and science popularization in China.

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