Towards Disseminating and Re-imagining Historical Stereoscopic Photographs through Contemporary Virtual Reality Platforms

Dhruva Gowda Storz
dhruva.gowdastorz@epfl.ch
École Polytechnique Fédérale de Lausanne (EPFL)
Lausanne, Switzerland

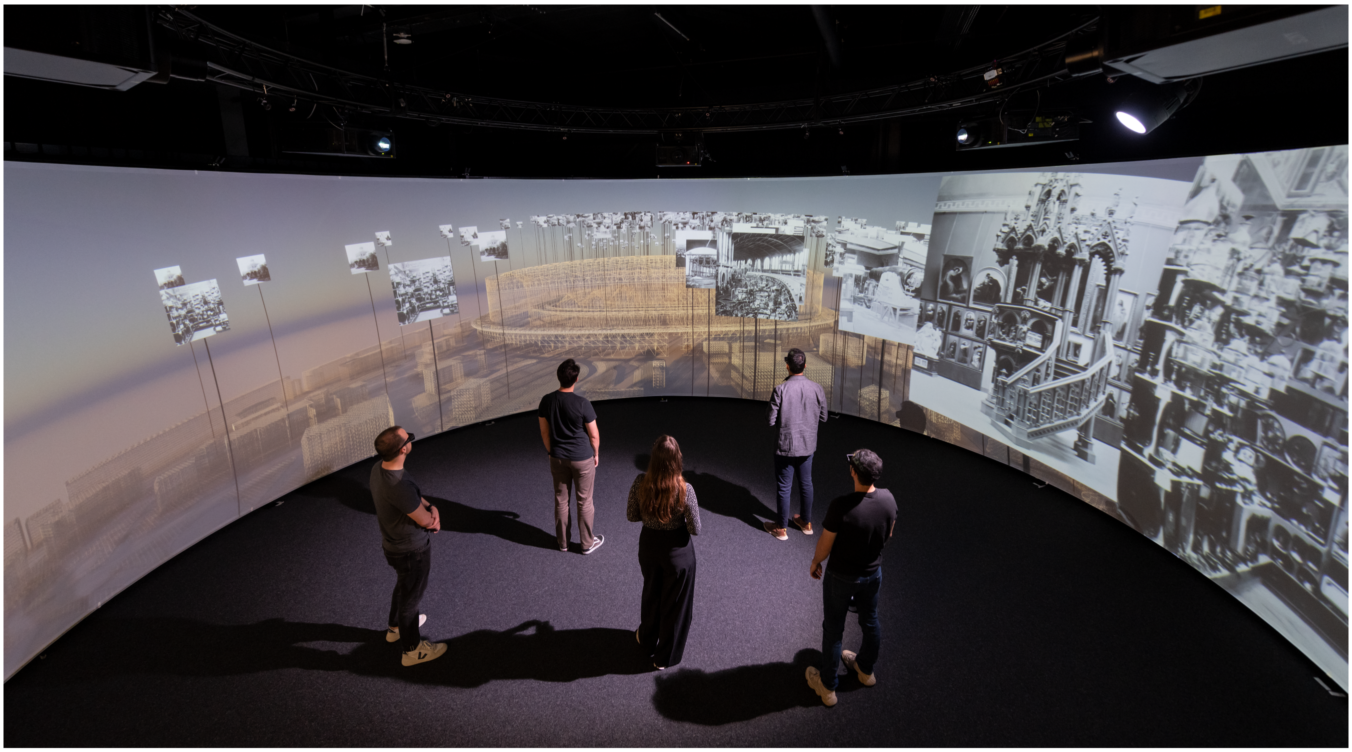

Figure 1: A prototype experience developed by our lab for visualizing historical stereographs from the Universal Exposition of 1867 running on our Panorama+ stereoscopic virtual reality system. Image copyright: the Laboratory for Experimental Museology (eM+) EPFL.

ABSTRACT

Stereoscopic Photography was the first 3D immersive medium and a prominent cultural phenomenon in the 19th and 20th centuries. Despite its importance in media history and its influence on visual culture and the immersive technologies that came after it, millions of stereographs are locked away in archives with no means of engaging with them in their intended three-dimensional viewing format, largely due to their reliance on a device to reproduce the stereo illusion. The rising ubiquity of virtual reality presents a platform to visualize and reimagine this forgotten medium while opening virtual reality up to a large quantity of content from the past. However, many of these photographs have sustained damage in the decades to centuries since they were captured, which generates discomfort when viewing them on high-resolution displays. The cost of manually restoring this damage for viewing is a significant barrier to their dissemination on contemporary virtual reality platforms. My PhD aims to surmount this barrier by developing an automatic restoration pipeline for historical stereographs and investigating how this historical material could be reimagined using modern 3D representations and techniques, bridging the virtual reality of the 19th century and the virtual reality of today.

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CCS CONCEPTS

• **Applied computing** → **Arts and humanities**; • **Computing methodologies** → *Image manipulation.*

KEYWORDS

Image Restoration, Stereo Photography, Stereo Restoration, Virtual Reality, Digitization, Archival

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1 INTRODUCTION

Stereoscopic photography, or 'Victorian Virtual Reality', was the first 3D immersive medium, and a direct ancestor to contemporary virtual reality systems. Much like virtual reality today, stereography was the center of a cultural craze in the 19th and 20th centuries, which lasted nearly 100 years, and had a vital impact on visual culture and the entertainment media that succeeded it. By simultaneously capturing two side-by-side images, stereoscopic photographs (or stereographs) capture not only visual information but a three-dimensional imprint by encoding depth information in the differences between the two images. When viewed in a specialized viewer called a stereoscope, the viewer is immersed in this three-dimensional imprint, allowing them to experience a moment in time as experienced by the photographer (Figure 2).

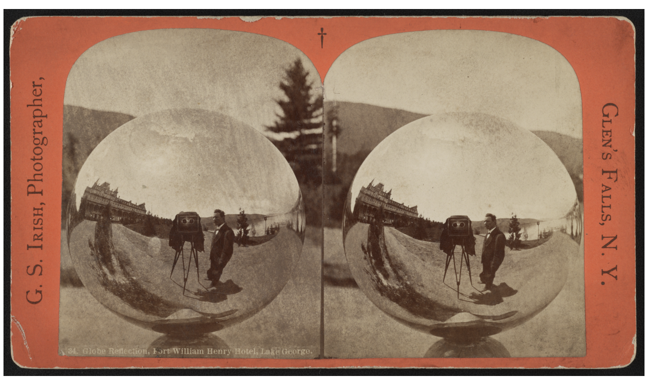

Figure 2: A stereo self portrait reflected in a globe, 1870, Photographed by G. S. Irish [Public domain], via Library of Congress (https://www.loc.gov/item/2011646046/)

Stereoscopy, the technique for creating and viewing 3D images, predates commercial photography. Sir Charles Wheatstone invented stereoscopy after discovering the mechanism for binocular depth perception in 1832. Shortly after the invention of the daguerreotype and Talbotype in 1841 (the first publicly available forms of photography), he commissioned the first-ever stereo photograph of Sir Charles Babbage [11]. Stereography quickly took off and became immensely popular in the Western world, spreading from Victorian London to Paris and eventually the United States. Throughout its period of popularity, several million stereographs depicting a wide variety of subjects were captured, including travel photography [8], historical events such as the First World War [17], and scientific and educational subjects [10], among many others. Several million of these stereographs still survive in the special collections of archives around the globe, many of which have been digitized and are publicly available through online portals. These archives are a treasure trove of three-dimensional historical records with much to reveal not only in terms of history but also through diverse topics such as media archaeology and the nature of immersion. Through these virtual worlds from the past, we can travel back in time to witness the construction of the Eiffel Tower, experience India under colonial rule, or see the bustling streets of New York in the early 1900s. However, despite stereography's significant impact and popularity, the medium has largely faded into obscurity.

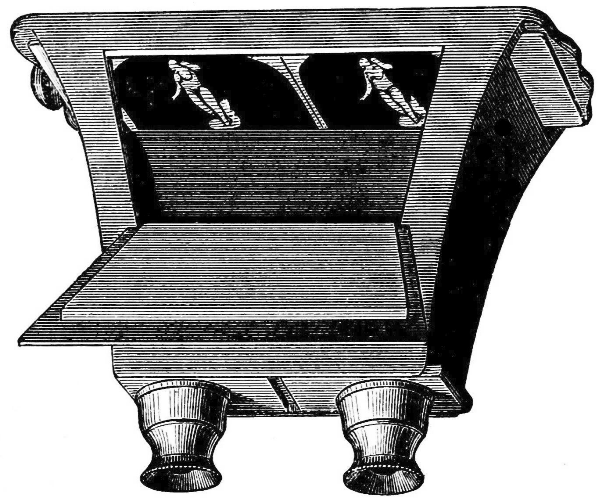

Figure 3: The Brewster Stereoscope, 1849. Image sourced from the Popular Science Monthly vol. 21, 1882 [public domain] via Wikimedia Commons

Many today see 3D immersive visualization as a modern invention and are surprised to learn that the field is so old, much less that stereographs were the center of such an enormous cultural craze. Stereography's disappearance from public awareness also extends to the academic domain, where the medium has largely been excluded from academic discourse and the histories of photography and has only recently resurfaced with the re-emergence of immersive media. It could be argued that stereography's downfall to cinema and conventional photography and its eventual fading away from the public consciousness is largely due to its reliance on a specialized viewing device to recreate the stereo illusion [7]. When its popularity began to wane, the 3D information encoded in stereographs was discarded by cutting them in half and printing them individually or projecting them in magic lanterns (an ancestor to cinema) [12], and the stereoscopes required to view them became rarities, making it increasingly difficult to engage with them. Today, this reliance on a device remains the primary obstacle to their dissemination.

Despite the wealth of stereographs available online, disseminating them beyond a small circle of enthusiasts and academics proves difficult due to the difficulty of transmitting the depth information they contain. Today, digitized stereographs are most commonly viewed as side-by-side pairs on a computer screen through online library portals or printed in books, which fail to immerse the observer in their three-dimensional historical contexts. The use of a stereoscope, although historically authentic, requires physical access to the stereograph, making it inaccessible to the larger public and risks jeopardizing the physical integrity of these fragile artifacts. The most common way to view stereographs in 3D is by processing them into a color anaglyph composite image and viewed through red/cyan glasses. Due to the low cost and accessibility of this method, it remains highly popular. However, these anaglyphs bear little resemblance to the often high-fidelity originals since they rely on creating a destructive composite image and are not as compelling as comparable visualization methods [20]. While existing methods are insufficient to facilitate the widespread dissemination of stereographs to the general public, the increasing ubiquity of virtual reality hints at a possible renaissance for the stereographic medium.

1.1 Disseminating Historical Stereographs through Virtual Reality

Contemporary virtual reality systems are descendants of stereoscopic photography and operate on the same principles. The craze around immersive visualization and virtual reality, as well as the increasing ubiquity of such systems in personal, commercial, and museological spheres, presents a unique opportunity to disseminate historical stereographs while opening up virtual reality to an incredibly rich and expansive wealth of content from the past.

Today's head-mounted displays retain a strong conceptual and morphological proximity to stereoscopes of the past (Figure 3). They are increasingly found in museums and homes, making them well-suited for visualizing historical stereographs. Other, more powerful forms of virtual reality such as the Panorama+ system[1] at our Laboratory for Experimental Museology allow for collaborative viewing without a cumbersome personal headset and are especially well suited to visualizing this material in a museum context. Advancements in the display quality and comfort of such systems are well suited to displaying stereographs in high fidelity. The computing power these systems have access to presents new ways to reimagine and visualize the 3D information encoded in stereographs and allow users to interact with them in new and interesting ways, making such devices a strong candidate for reviving the lost medium. However, there remains one major obstacle to this: The damage sustained by stereographs and the discomfort this generates when viewed in 3D.

1.2 Restoring Historical Stereographs

Historical stereotypes in archives exist in various conditions, but many are more than 150 years old and have accrued significant damage due to handling, age, chemical alterations, and other factors. Unlike monoscopic photographs from the past, where damage can easily be ignored, damage to stereographs generates significant discomfort when viewing them in 3D, as the damage is not consistent between our two eyes. The asymmetries between the two images conflict with our brain's attempt at reconciling them to a stable three-dimensional view and leads to a phenomenon called retinal rivalry [5], Which can be deeply uncomfortable to look at [14]. This is especially true when working with high-fidelity images and displays like those increasingly used in virtual reality systems.

In addition to deteriorating the quality of experience of viewing stereographs, visual discomfort in stereo can even affect viewers' emotional response to the image's content [3]. As a result, the quality of experience and degree of immersion afforded by historical stereographs hinges on the correction of any asymmetrical damage they contain to improve their viewing comfort. Beyond restoring, stereographs also need to be cropped out of the stereo cards housing them and aligned before viewing on a stereoscopic display. Today, digital restoration professionals manually process stereo pairs before they are displayed. This painstaking task can be prohibitively time-consuming and expensive when working on a larger corpus. These constraints often affect the curation and dissemination of stereographs as discarding or aggressively cropping material is often easier and more cost-effective than restoring them, and restoring the larger body of stereographs worldwide would require significant funding, manpower, and time. This is a substantial barrier to disseminating historical stereographs.

Developing an automated system for processing historical stereo pairs would contribute significantly to liberating these priceless historical records from the archives in which they are confined. Such a system could drastically reduce the cost of processing historical stereographs, improving the ease and practicality of working with them and facilitating their widespread dissemination through virtual reality. The development of such a system lies at the core of my proposed PhD research.

1.3 Aims and Scope

The aim of my PhD, which is in its early stages, is to facilitate the dissemination of historical stereographs through virtual reality and explore how dissemination could be encouraged by elevating them beyond their intended viewing format through the development of various augmentation techniques. We aim to do this by developing a stereo-specific restoration and augmentation toolkit comprised of an end-to-end automatic restoration pipeline and a set of augmentation tools. Through the development of this toolkit, we aim to answer three research questions:

- **RQ1 (restoration)**: How can we partially or fully automate the restoration of historical stereo photographs to improve their comfort when viewed on stereoscopic displays?
- **RQ2 (augmentation)**: How can we use computer vision and visualization techniques to augment historical stereographs beyond their intended viewing format to enhance and encourage their dissemination?
- **RQ3 (visualization)**: How can we visualize stereographs and their augmented representations in virtual reality in new and interesting ways?

Our proposed methodology will be described in more detail in section 3.

2 RESEARCH CONTEXT

The visualization of historical stereographs remains a niche topic in the academic community. Still, the difficulty in disseminating historical stereographs has not gone unnoticed, and the potential

[1]For more information on the panorama+ visualization system, see page 16 at https://www.epfl.ch/labs/emplus/systems/

for virtual reality to this end has been increasingly explored in recent years. Researchers and Institutions have explored the use of smartphone-based virtual reality devices [6, 24], Augmented Reality [21], and other innovative interactive techniques [22, 23] towards finding new ways to visualize and disseminate historical stereographs. However, these projects are limited to visualizing small, curated collections of stereographs and do not fully utilize the potential of today's high-end virtual reality systems. Projects working with larger-scale historical stereograph datasets are fewer and farther between. Notable among them is [16], which attempts to create a large dataset of 37,239 processed and rectified stereographs from the Keystone-Mast Collection paired with disparity maps and metadata, along with Slow Glass, a motion-cue-based visualization method for viewing 3D images on a 2D screen.

Research into sources of visual discomfort in stereo content and how to address them has been an active area of research for several decades, largely fuelled by the post-processing needs of the 3D cinema industry [4, 18], and has been accelerating in recent years [25], perhaps due to users of today's VR devices suffering greatly from discomfort and visual fatigue. Despite this interest in improving the visual comfort of stereo images, damage-based discomfort is highly specific to historical stereo images and has seen little attention from researchers.

Automatic restoration methods are mostly limited to the monoscopic domain [2]. While some methods are highly effective for conventional photographs [26], these methods do not consider the stereo context and risk introducing new sources of asymmetry when correcting damaged stereo images. The automatic restoration of historical stereographs remains an extremely niche field, and to the best of my knowledge, only one methodology for stereo-specific restoration exists in the literature [9]. While their results are promising, this work focuses more on restoration for visual improvements than comfort optimization for stereoscopic viewing, leaving room for improvement.

Research into visualizing historical stereographs on virtual reality systems remains a burgeoning field, but none of the projects in this domain have linked virtual reality and stereo restoration. Although 3D cinema post-processing provides a strong backbone for improving the viewing comfort of stereographs and existing stereo restoration algorithms serve as a good reference point for future work, these disjointed methods are not designed in the scope of an end-to-end restoration system, which leaves much work to be done on the restoration front. Therefore, this PhD's goals are unique in scope, breadth, and depth and would unite several disparate but related research fields under one project.

3 METHODOLOGY

This section presents our proposed methodology for developing and assembling our toolkit for virtualizing historical stereoscopic photographs. The methods in this section fall under three categories: Restoration, Augmentation, and Visualization, each of which will be described in detail in the following sections.

3.1 An End-to-end Restoration Pipeline for Historical Stereographs

Restoration is the core research area of this PhD. It aims to address the monetary, time, and labor costs involved in digitizing and processing historical stereographs for visualization on modern stereoscopic displays. We propose to address this by developing an end-to-end pipeline for the damage restoration, alignment, color correction, and comfort optimization of historical stereographs for viewing on contemporary virtual reality platforms. As the pipeline is intended to facilitate the dissemination of as many stereographs as possible from around the world, it has the following requirements:

- **Robust:** The pipeline needs to work well on a broad range of stereographs containing various defects and at various resolutions.
- **Efficient:** The pipeline needs to operate fast enough to make the processing of large archives feasible.
- **Accurate:** As much as possible, the pipeline should use known information when restoring defects, and not introduce new hallucinated content unless necessary.

It is also vital for the pipeline to respect the historical context and identity of the stereographs it works with, and it will be designed with the perspectives of archival and restoration in mind. To begin with, the pipeline will retain the original image in its outputs as much as possible, maintaining the relationship between the original and the processed stereographs. It will have detailed annotations of the processing applied at each stage such that any alterations can be traced and the restored images are not removed from their original context. Furthermore, the pipeline will be designed to be modular, giving users the option of using each of its stages independently when desired. Finally, we aim to minimize the use of deep-learning-based generative AI techniques as these systems tend to 'hallucinate' content, which risks altering historically important content in our photographs.

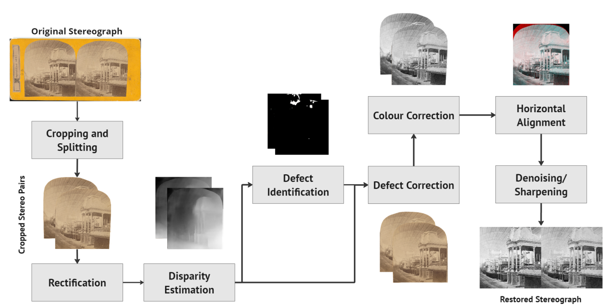

Figure 4: Structure of our proposed pipeline, with illustrative processing of a stereograph. Image by Leon & Levy [Public domain], via Library of Congress (https://www.loc.gov/pictures/item/2005675985/)

Figure 4 depicts a diagram of the proposed pipeline, detailing how a sample stereo image would be processed step by step. The proposed structure of our restoration pipeline was determined based on informal interviews with restoration professionals, through which eight key steps were identified in their workflows. Each step will be automated through the careful development or selection of algorithms. These eight steps are as follows:

- **Cropping and Splitting** Seperates the two images from their stereo card for further processing
- **Rectification** Translates and rotates each stereo pair relative to each other to align epipolar lines for easier disparity estimation and eliminating viewing discomfort from vertical misalignment
- **Disparity Estimation** Computes pixel correspondences between the two rectified stereo pairs through stereo disparity estimation or optical flow methods
- **Defect Identification** Identifies which pixels in each stereo pair contain structured defects using visual information and pixel correspondence from the previous step
- **Defect Correction** Inpaints damaged pixels in one stereo pair using data from the corresponding pixels in the other undamaged stereo pair. In the case that corresponding pixels in both pairs are damaged, performs symmetric generative inpainting of both.
- **Colour Correction** Addresses global yellowing and fading, converts to black and white, and corrects local and global exposure differences between the two stereo pairs.
- **Horizontal Alignment** Shifts the two images relative to each other to establish an optimal zero disparity point to reduce viewing discomfort arising from depth budget issues. This will be followed by another round of cropping to address any window violations generated by the alignment.
- **Denoising** Removes unstructured defects such as haze or abrasion damage not addressed by the defect correction step and improves the visual quality of the image by removing noise and sharpening it.

The first six steps are currently being developed in collaboration with the EPFL Center for Imaging.

3.2 Augmenting Stereographs Beyond 2D

While the restoration facet of my PhD aims to restore stereographs to their original condition while preserving their historical context as much as possible, the augmentation methods we develop will investigate how these restored stereographs can be transformed through contemporary computer vision and AI techniques. While this area of the PhD remains open-ended, two key augmentation modalities that will be investigated are AI-recolouring and 3D reconstruction.

3.2.1 ***AI (Re) Coloring.*** As most stereographs found in archives are black and white, they benefit greatly from being recolored. Coloring a historical stereo pair not only improves a stereo image's visual quality but also improves viewing comfort, as consistent coloring helps reduce asymmetries between two stereo pairs, even helping counteract the discomfort caused by damage. Recoloring models such as DeOldify [1] are highly effective and robust and would be effective additions to our toolkit. However, these models fundamentally hallucinate the colors they assign and are generally biased toward the datasets they were trained on, which are seldom representative of real-world historical images. There is, therefore, room for a great deal of research into historically grounding these models for use in an archival context, for example, by incorporating a human-in-the-loop editing system or allowing it to be conditioned on reference images of surviving objects or illustrations from the time. These recoloring models and the challenges surrounding recoloring from an archival perspective will be investigated under the scope of this PhD and incorporated into the pipeline.

Figure 5: A 3D point cloud generated from a stereograph

3.2.2 ***3D reconstruction.*** A more complex but potentially more powerful way of augmenting stereographs is through 3D reconstruction. The third step of our proposed restoration pipeline involves calculating pixel correspondences (disparity) between pixels in each stereo pair. This process alone satisfies the base requirements for reconstructing a 3D scene from the stereo pair. By projecting each pixel in 3D space based on its disparity value, we can generate a basic point cloud from a stereo pair (figure 5). Converting stereo images into other 3D representations, such as point clouds, could enable new ways of reimagining and visualizing historical stereo photographs. Imagine walking through a scene from the past instead of merely viewing it through a window.

However, the point clouds generated through this method are sparse and lose their structure as you view them from angles other than the one used to capture them and are not as compelling in this form. To make them explorable, they need to be densified, and missing areas need to be inpainted, which is a non-trivial task. State-of-the-art modes of 3D representations such as Neural Radiance Fields [19] and Gaussian Splatting [13] may offer a better way to generate explorable 3D scenes from a collection of images. While these methods typically require far more images than we have access to with a single pair of stereo images, recent algorithms are now capable of reconstructing scenes from as few as three photographs [27], and a future where this could be done with only two stereo images might be close.

3.3 Visualization

Visualization is the third and final theme of research within my PhD. Several interactive VR visualization prototypes will be created throughout the PhD as a byproduct and an end goal of the restoration and augmentation themes. These visualizations will primarily be used to evaluate the efficacy of our restorations and augmentation tools, as well as the degree of improvement to visual comfort and QoE that they impart, through methods and metrics such as [15]. Both screen-based and HMD experiences will be built, as our proposed toolkit will be designed to process material for both types of systems.

These prototypes will also serve as demonstrators for the potential of virtual reality for viewing and reimagining historical stereographs. Figure 1 shows an example of one such prototype that was developed at our lab for our Panorama+ system. These demonstrators could be used to promote historical stereo pairs, serve as foundations for future work in visualizing stereographs restored by our toolkit, and allow us to determine the best interaction modalities, interfaces, and general design guidelines that facilitate optimal engagement with this material on virtual reality systems. Evaluating these demonstrators is a good way of determining the success of our project and the value it brings to disseminating historical stereo photographs.

4 CONCLUSION

In conclusion, this research aims to revolutionize the way we interact with historical stereoscopic photographs by leveraging the capabilities of contemporary virtual reality (VR) platforms. The proposed end-to-end restoration pipeline seeks to overcome the barriers of cost and labor associated with manual restoration, thus enabling the widespread dissemination of these cultural treasures. Additionally, the exploration of novel augmentation techniques promises to enhance the viewing experience beyond traditional formats, potentially allowing users to step into and explore historical scenes in immersive 3D environments. The successful implementation of this project will not only preserve and breathe new life into historical stereographs but also enrich the content available for VR, bridging a gap between the past and the present. This work stands as a testament to the enduring legacy of stereography and its significance in the evolution of immersive media.

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