Towards Realistic Light Field Experiences: Camera Animation, User Interaction, HDR Reconstruction, and Quality of Experience

Theses of the Ph.D. Dissertation

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2024

1 Aim and motivation

Visualization plays a pivotal role in enhancing our understanding of complex information, enabling clearer insights and informed decision-making across a range of disciplines. Among novel capture and visualization technologies, Light Field (LF) has made significant advancements, edging closer to everyday applications. LF technology has emerged as a means of representing the 3D world – to which it acts as a window – by light rays filling up the 3D space under representation [1]. Light Field Display (LFD)s were developed to visualize the captured LFs [P4]. Unlike many 3D display systems, LFDs deliver a complete 3D experience without requiring personal viewing devices. Due to the lack of such constraint, these displays may be viewed by any number of observers simultaneously, and the corresponding use case contexts may also involve a virtually unlimited numbers of users; any number that the Valid Viewing Area (VVA) of the display may accommodate [P1; P2].

While many uses of LF technology focus on static content, the potential for dynamic camera animation in LF visualization remains largely uncharted. Camera animation in LF technology is a crucial but underexplored area, especially relevant to applications like cinematography. Unlike conventional 3D camera animation where motion techniques are often straightforward, LF visualization presents distinct constraints and challenges that complicate any implementation of camera movements. The intricate mechanics of LF cameras reveal obstacles that may limit flexibility in capturing dynamic scenes, hinting at complex underlying limitations that are yet to be fully understood.

Despite the numerous advantages and attractive capabilities of such glasses-free 3D displays, the design relevant for their User Interface (UI) presents a series of complex challenges, falling short of the intuitive ease provided by conventional 2D displays. A critical limitation is that visual feedback can be rendered sharply only on the emission surface of LFDs, constraining the clarity and responsiveness of interactions. The complexity of UI design for these displays suggests that creating effective presentation models – ones that can integrate navigation, selection and manipulation, and application/system control – may require overcoming unique barriers that are yet to be addressed.

The third area of exploration delves into High Dynamic Range (HDR) LF imaging; a frontier where the potential for heightened realism of HDR meets the immersive depth of multi-autostereoscopic systems like LFDs – all without the need for viewing gear. While merging HDR and LF imaging holds promise for creating vivid, engaging experiences across diverse applications, this integration poses significant challenges. The distinct limitations of both HDR and LF technologies raise questions about how – or rather, if – these two powerful methods can effectively work together without compromise.

Finally, as projection-based LF visualization technology advances, a key challenge remains in understanding human observer experience, largely due to the lack of standardized testing methodologies. While the immersiveness and 3D perceived quality of LF technology promise significant impact across areas such as cinematography, medical imaging, digital signage, telepresence, and industrial and military applications, ensuring a high Quality of Experience (QoE) requires careful evaluation. Achieving reliable measures of user satisfaction typically involves subjective tests that examine both individual and combined experience factors. Yet, essential questions remain about the specific elements that shape visual experiences on LFDs and how these vary across diverse user groups and use cases, leaving a critical gap in understanding user perception in this evolving field.

In the upcoming section, I will address the challenges identified in LF technology by focusing on four key thesis points: LF camera animation, interactive UIs, HDR LF imaging, and the subjective evaluation of QoE across different LFDs. For each point, experimental results will be presented to support proposed solutions, with the aim of advancing the state of LF visualization. These findings will demonstrate how the challenges in these areas can be overcome, contributing to the improved quality, usability, and accessibility of LF technology.

2 New scientific contributions and thesis points

The primary scientific contributions of this dissertation are articulated in the following key theses:

Thesis 1 *Light field camera animation* **(Chapter 3)**

Related publications: **[P5; P4; P1; P2]**

To advance the study of camera animation in LF visualization, I designed and developed a novel simulation framework that uniquely incorporates the properties of LF cameras, rigorously testing it on a real LFD. Through this framework, I established a foundation for LF camera animations –an underexplored area– by developing and testing various virtual camera animations on a Horizontal-Only-Parallax (HOP) LFD, namely the HoloVizio C80 cinema system, thereby paving the way for future research.

Main features of this work are as follows:

- This new and original framework, built using Holografika's clustered rendering modules, is the first to support both lenticular and projection-based displays while utilizing a GPU cluster for real-time, multi-view rendering optimized for HoloVizio LFDs.
- This simulation framework enables real-time rendering of diverse scenarios, simulating physical environments and common camera movements used in film production.
- I integrated path planning for wide-baseline LF cameras and physical camera simulation, allowing users to set key parameters like speed, mass, and acceleration for camera movements.
- Optical and sensor properties are automatically aligned with the LFD to ensure seamless compatibility between LF cameras and displays without the need for additional conversions.
- Through the framework, I addressed the challenge of matching captured LFs with those of the LFDs by means of virtual LF cameras, with findings applicable to physical LF cameras with comparable baselines. I managed the camera movement by means of Region Of Interest (ROI) matrix, where display rays were evaluated and transformed into world space coordinates, making it easier to render objects and lights within the same system.

- I defined the capture surface of the LF camera by determining sensor positions per pixel and tessellating a flat surface among neighboring points. I devised error metrics to evaluate system performance on LFDs by using a 4×4 affine transformation (ROI) to align observer and capture planes.
- I created realistic simulation environments using the Bullet Physics Library [2] to model physical scenes with basic shapes. The framework tested various camera animation scenarios by adjusting parameters like weight, size, and motion for both cameras and scene objects. This helped generate diverse scenarios to assess the effectiveness of different camera movements for LF camera simulations.
- I implemented different camera animations to establish the foundation of LF camera animations for LF visualization. Camera animations included cinematography camera animations including pan, tilt, zoom, dolly, truck, and pedestal. Additionally, I created simulation camera animations for both first- and third-person perspectives. I also developed three physical scenarios to simulate collision, falling, and suspension cameras.
- I developed a set of criteria to assess different aspects of camera animation including general visibility of the scene along the observer's line during animations, the frequency of immersion-breaking occluders, collision occurrences, depth-related artifacts, and changes in the depth of field. Based on the results of the expert assessments, I identified which LF camera animations are suitable for LFDs and which require further investigation.
- Results of perceptual assessments indicated that pan, tilt, truck, and pedestal camera movements produced clear outputs, while dolly and zoom movements caused blurriness. First-person camera simulations also showed artifacts, while third-person camera animations were more reliable. These findings pave the way for future LF camera animations, highlighting effective camera movements and areas for refinement to enhance visual quality and user experience.
- To evaluate the plausibility of the generated physical simulations (i.e. collision, falling, and suspension cameras), I devised several objective metrics to be measured, designed for HOP LFDs:
  - Camera collision metric: counts the number of intersections between the Axis-Aligned Bounding Box (AABB)s of the objects in the scene and the AABB of the camera.

  - Blurriness metric: measures the number of blurry objects in the scene by counting the intersections between the objects' AABBs and the frustum defining the blurry region of the LFD.
  - Occlusion metric: used in case of third-person cameras.

- I conducted subjective tests to further evaluate the plausibility of the realistic physical simulations. The results showed that 76.2% of participants preferred third-person cameras on LFDs due to the blurriness and discomfort caused by first-person cameras, which also led to dizziness and focus loss, indicating the need for further research.

- A key finding in the subjective assessment was the inverse relationship between participant movement and camera motion. Evaluations revealed that increased camera motion resulted in more occlusions, blurriness, and collisions, which reduced visual quality. Based on these findings, slight camera movements are recommended for LFDs.

- Beyond the implemented framework, I theoretically explored the development and assessment of LF camera animation techniques, analyzing their implications, limitations, potential applications, and directions for future research from the perspectives of use cases, visual content, quality assessment, and capture and display hardware.

Thesis 2 *Interaction techniques for light field displays* **(Chapter 4)**

Related publications: **[P6; P4]**

In order to test different interaction methods on LFDs, which have thus far only seen the development of basic UIs, I first analyzed the challenges imposed by LFDs for each of the 3D interaction tasks (i.e., navigation, selection and manipulation, and application/system control). Then, I proposed several presentation models for LFDs, including line-up, carousel, 3D sphere, CAD/CAM, medical, and theater model, where the latter was chosen.

I implemented a theater model using *MAYA*[1], and visualized it on the HoloVizio C80 LFD. The theater model was selected because it parallels LFDs, allowing multiple viewers to observe content simultaneously in an angularly-dependent manner. Considering the capabilities and limitations of LFDs, I analyzed and modified the three interaction tasks involved in 3D environments as follows:

- **Navigation** in LFDs, due to their multi-camera setups, presents unique challenges that require modifications to the observer line/rectangle, for precise adjustments. To address this, I implemented a static camera configuration designed to meet these requirements within the theater model.
- In the theater model, I implemented several selection and manipulation techniques, including a rotating stage positioned in the sharp region of the LFD to prevent blurriness during movement. I also animated objects along designated paths and used curtains to hide/reveal elements. To avoid transitioning into blurry regions, presentation elements were positioned on a plane parallel to the screen (e.g., animating curtains and flying systems). Additionally, I employed rotating stages with one half in the sharp region and animated spotlights within a limited range to minimize LFD issues.
- **Application/system control** on LFDs is challenging, as overlay rendering relies on image space, which disrupts the 3D depth perception essential to LFDs. I proposed several possible solutions including rendering the UI into 2D areas, akin to selection methods, or spatially separating 3D controls from the main scene to provide scene feedback on the control geometry. In my work, I implemented a monitor room to

[1] `https://www.autodesk.com/products/maya`

provide high-quality visual feedback. View switching is triggered by pressing buttons, which activate corresponding animations and lighting in the theater model. The monitor room displays the current view, and after activation, navigation resumes through a static camera within the theater model.

I conducted subjective assessments of the three implemented theater scenarios to gather feedback data, which is crucial for the long-term development of such applications. The following summarizes the novel findings for each interaction task:

- I evaluated user preferences for the **navigation** task, finding that the majority of participants favored a static camera. This preference appeared to enhance the 3D effect of the LFDs, with further improvement achieved by allowing users to move around the screen. My findings suggest that static cameras are effective for navigation tasks, as they reduce discomfort while preserving immersion.
- I assessed interaction models for **selection and manipulation** on the LFD, finding a strong preference for the “multiple carousels” model, along with positive responses to “curtain” and “flying system” motions and backstage theater scenes. These findings indicate a clear preference among participants for highly interactive methods on LFDs, with increased interest in moving around the display for better immersion. Overall, participants favored interaction techniques on LFDs over traditional 2D displays and expressed a desire for more advanced interactive features.
- I assessed user preferences for the **application/system control task** and found that most participants preferred buttons within the main scene, although this could disrupt 3D immersion. This highlights an ongoing challenge in providing effective feedback for 3D scenes, offering insights for future immersive system design.

Finally, subjective evaluation revealed an inverse relationship between the level of interaction on LFDs and participant mobility.

Thesis 3 *Towards HDR light field imaging* **(Chapter 5)**

Related publications: **[P7; P8; P9; P10]**

In this thesis, I integrate both HDR technology and multi-autostereoscopic systems, such as LFDs, to achieve powerful and impactful results, while also examining the potential challenges. HDR technology enhances the realism of visual content, while multi-autostereoscopic systems deliver immersive 3D experiences without the need for specialized viewing equipment.

To achieve HDR LF imaging, the following steps were undertaken:

- I carried out a comprehensive analysis of HDR LF imaging applications and explored future use cases with substantial practical potential. Key applications examined include physically-based rendering, digital photography, image editing, cinematography, various medical use cases, cultural heritage, education, digital signage, and telepresence.
- Reconstructing HDR LF content from Low Dynamic Range (LDR) LF images poses challenges but can yield higher-quality outputs, as scene information is encoded across multiple images. In my work, I investigated the theoretical possibilities of combining Convolutional Neural Network (CNN) architectures utilized for HDR images and videos, in order to enhance the outputs of HDR LF image reconstruction.
- As a starting point for LDR-to-HDR LF reconstruction research, I tested several HDR reconstruction CNNs on the *Teddy* LF image dataset [3]. The insights gained from the output images have provided valuable guidelines for developing CNNs for HDR LF image reconstruction.
  - I found that *ExpandNet* [4] produced visually plausible images, though it introduced ghosting artifacts in the background. This suggests that integrating concatenated feature branches could improve the model's adaptability to various datasets.
  - I discovered that *HDR-DeepCNN* [5] exhibited color inconsistencies, likely due to skip connections involving domain transformations from LDR display values to logarithmic HDR.
  - I observed that *DeepHDRVideo* [6] exhibited visible artifacts in shape and texture, which can be attributed to alignment errors in optical flow.
- I evaluated the performance of the CNNs using three objective metrics: (i) Peak-Signal-to-Noise-Ratio (PSNR), (ii) Structural Similarity Index

Measure (SSIM), and (iii) HDR-Visible Difference Predictor (VDP). The following findings were observed:

  - Results showed that *DeepHDRVideo* achieved the highest PSNR and SSIM scores, while *HDR-DeepCNN* excelled in HDR-VDP scores, better aligning with the Human Visual System (HVS). This was reflected in the reconstructed HDR images, which exhibited superior consistency and visual quality.
  - Although video reconstruction techniques were expected to perform well by leveraging temporal coherence –analogous to spatial coherence in LF images, results show that *HDR-DeepCNN* ultimately delivered more convincing quality results.
  - These findings highlight the need for developing more HDR LF datasets and creating quality metrics tailored to evaluate the unique characteristics of LF imaging.

- I developed a synthetic HDR LF dataset called "CLASSROOM" to address the limited availability of such datasets for CNN training and testing. This dataset allows manipulation of various parameters and scene complexity, supporting the creation of additional datasets. It is not limited to a specific baseline or parallax, enabling the generation of datasets with varying configurations, thus advancing the field of HDR LF reconstruction. I created the "CLASSROOM" dataset using *MAYA* 2022 and rendered it with the Arnold renderer, considering both narrow- and wide-baseline systems. I created the following datasets:

  - A narrow-baseline Full Parallax (FP) dataset with 5×5 images.
  - A narrow-baseline HOP dataset, a subset of the first with selectable rows.
  - A wide-baseline HOP dataset with 15 images.

  I calculated the inter-image distance based on the Field Of View (FOV) of the LFD, the number of images, and the distance between the display and observer's line/rectangle. To create the narrow- and wide-baseline datasets, I adjusted the camera's focal length to 35 mm and 20 mm, respectively.

Thesis 4 *Quality of experience for light field visualization* **(Chapter 6)**

Related publications: **[P11; P12; P13; P14; P15]**

This thesis incorporates subjective studies that evaluate a range of factors impacting the visual experience on LFDs, both broadly and within specific use cases, involving participants with both normal and reduced visual capabilities. In these experiments, I rendered the content on the LFDs and conducted the experiments.

Experiment 1: Regarding LFDs, the optimal viewing distance remains an open research question. Building on the findings by Kara *et al.* [7], the study investigates both **perceptually-supported and subjectively-preferred viewing distances for LF visualization**, conducted on the HoloVizio 80WLT LFD and HoloVizio C80 cinema system.

- I used the Holo Qt Converter to render content for the perceptually-supported viewing distance experiment and Holografika's clustered renderer for the subjectively-preferred experiment, generating ten source contents. I conducted each experiment twice, once with experts and once with 22 regular participants.
- The perceptually-supported viewing distance experiment showed that experts preferred distances between 4 m and 5.75 m, while non-experts favored 3.5 m to 6.75 m. Although some outliers existed, their subjectively-preferred viewing distances aligned with other participants.
- Outliers were observed to be taller than other participants, which impacted the results due to the larger horizontal displacement at their eye level. To account for this, the maximum viewing distance threshold for LFDs is recalculated as $D_V = \frac{D_E + D_S}{tan(AR)}$, where D_S accounts for the horizontal displacement from participant swaying.

Experiment 2: For complex models, angular resolution plays a critical role, as insufficient resolution can result in crosstalk, while higher resolution may improve detail. On the other hand, deeper 3D rendering can still lead to blurriness. The interconnection between these factors highlights the need for careful optimization to achieve the best visualization quality. Therefore, this experiment investigates the **effect of angular resolution and 3D rendering on the perceived quality of content in LF visualization for industrial contexts**, particularly for prototype evaluation, given the complexity of industrial models.

- I conducted the experiment on the HoloVizio HV640RC LFD. I rendered 7 different static industrial objects at 7 angular resolutions (ranging from 0.5 to 2 degrees), with a fixed spatial resolution of 1024×768. The experiment used the hidden reference method and involved 43 participants.
- The results showed that source contents with greater depth variations were more affected by reduced angular resolution. Minor inconsistencies in similar test conditions were noted but had little impact.
- Overall, both angular resolution and 3D rendering significantly influenced the QoE, with quality ratings being directly linked to the classification based on the depth of the source content.

Experiment 3: As visual impairments become more prevalent among younger individuals, understanding how both unimpaired and impaired individuals perceive LF visualization quality is crucial. This study presents our preliminary investigation into **LF visualization as evaluated by participants with imperfect visual acuity and color blindness**.

- I conducted the experiment on the HoloVizio HV640RC LFD to examine various factors influencing LF visualization, with two participant groups: Group 1 consisting of 8 participants with impaired visual acuity and Group 2 consisting of 7 participants with color blindness.
- I rendered 8 static scenes with varying complexity, depth, textures, and structures, across 12 test conditions defined by 2 spatial resolutions (640×480 and 1024×768), 3 angular resolutions (1°, 0.66°, and 0.5°), and 2 viewing distances (1.86 m and 3.72 m).
- Results showed that viewing distance significantly impact perceived quality, with closer distances highlighting impairments, particularly blurriness from low spatial resolution. Statistically significant differences in spatial resolution were observed across all angular resolutions at the closer distance.
- Group 1 and Group 2 showed similar rating tendencies, but color-blind participants generally gave lower scores, especially at closer distances. In Group 1, angular resolution had a greater impact, while for Group 2, viewing distance was more influential.
- Rating inconsistencies, mostly related to angular resolution and content with minimal depth variation, were more frequent among color-blind participants. Diopter values did not significantly affect the rating inconsistencies.

Table 1: Overview of the experiments addressing the QoE for LF visualization

Experiment	Visualization factors				Participants	
	Viewing distance	Angular resolution	3D rendering	Spatial resolution	Impaired visual acuity	Color blind
Experiment 1	✓	—	—	—	—	—
Experiment 2	—	✓	✓	—	—	—
Experiment 3	✓	✓	—	✓	✓	✓
Experiment 4	✓	—	—	✓	✓	—

Experiment 4: This study investigated the **preferred viewing distance for LF visualization among individuals with impaired visual acuity during static observation.**

- I used the same source material as in the previous experiment, excluding two scenes, to account for the large number of viewing distances. A total of 21 participants took part: 20 with high diopter glasses and one with more than 90% vision impairment. Six viewing distances were marked: 1.39 m, 1.86 m, 2.32 m, 2.79 m, 3.25 m, and 3.72 m. The study employed two quality settings: low resolution (640×480 spatial, 1° angular) and high resolution (1024×768 spatial, 0.5° angular).
- Results indicate a strong preference for greater viewing distances across both resolutions, with closer distances receiving lower ratings, especially at low resolution.
- Notably, the participant with over 90% vision impairment preferred closer distances, likely due to his/her impaired vision, which contrasted with the general trend observed in other participants.

Overview of the subjective studies: The experiments on QoE for LF visualization provided valuable insights into factors affecting perceived quality and user experience, contributing to improvements for general and specialized applications. Table 1 provides an overview of the factors and participants involved in each experiment.

3 Suggestions for future work

LF technology has advanced significantly, enabling the representation of 3D scenes through light rays. LFDs allow for glasses-free 3D viewing and multiple users to interact with the content simultaneously, though challenges remain in its practical application. This study addresses the challenges in advancing LF technology, and this section outlines the directions for future research and development to further propel its progress.

Light field camera animation. Camera animation in LF visualization is an emerging area of research with significant potential, particularly for dynamic applications such as cinematography. Despite its importance, this area remains underexplored, with several challenges related to the constraints of LF technology that require further investigation including:

- Further research is needed to identify optimal camera motion designs that minimize visual artifacts on LFDs.
- Various methods can be investigated to simulate first-person camera perspectives while mitigating artifacts arising from the inherent limitations of LFDs.

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Interaction techniques for light field displays. The design and implementation of UIs for LFDs remain complex due to constraints in visual feedback and interaction clarity. Future work include:

- Investigate additional presentation models on LFDs to further assess the feasibility and effectiveness of 3D interactions.
- Explore novel approaches for delivering application/system control feedback on LFDs, with the goal of displaying the Graphical User Interface (GUI) and providing feedback without compromising the 3D immersion.

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Towards HDR light field imaging. HDR LF imaging offers significant potential in various applications, particularly in medical fields where high-quality visuals are critical. However, the integration of these technologies presents challenges due to the inherent limitations of both technologies. Areas of future work include:

- Address the specific requirements of each use case for HDR LF imaging to optimize performance and applicability.

- Enhance LDR-to-HDR LF reconstruction by utilizing CNNs across multiple LF images, rather than single-image approaches, to leverage spatial coherence and angular information.

- Evaluate a broader range of CNN models to further enhance HDR LF reconstruction.

- Develop CNNs tailored specifically for LF imaging to improve HDR reconstruction quality and accuracy.

- Create a dataset for arc systems by rendering images from multiple orientations using *MAYA*.

- Investigate methods for capturing real-world HDR LF content to enhance the practical applicability and relevance of these datasets.

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Quality of experience for light field visualization. To improve the user experience in LF visualization, we conducted experiments across various LFDs to identify key factors influencing the visual experience. Future work include:

- *Experiment 1:* Investigate how observer movement varies across different use cases and assess the impact of natural sway during static observation.

- *Experiment 2:* Explore various use case contexts, emphasizing their unique characteristics, to deepen the understanding of LF visualization's impact in different scenarios.

- *Experiments 3 and 4:* The usage of LFDs over extended periods should be studied for perceptual fatigue, along with observer movement in passive and active use cases. Preferences for greater viewing distances, where 3D effects may become more 2D, should be investigated. Additionally, different motion models, including sideways movement and dynamic distance changes, should be examined, as well as the impact of adverse lighting conditions on visual perception, particularly for individuals with reduced visual capabilities.

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Acronyms

AABB Axis-Aligned Bounding Box. 4, 5

CNN Convolutional Neural Network. 8, 9, 14

FOV Field Of View. 9

FP Full Parallax. 9

GUI Graphical User Interface. 13

HDR High Dynamic Range. 1, 2, 8, 9, 13, 14

HOP Horizontal-Only-Parallax. 3, 4, 9

HVS Human Visual System. 9

LDR Low Dynamic Range. 8, 14

LF Light Field. 1–5, 8–14

LFD Light Field Display. 1–11, 13, 14

PSNR Peak-Signal-to-Noise-Ratio. 8, 9

QoE Quality of Experience. 2, 11, 12

ROI Region Of Interest. 3, 4

SSIM Structural Similarity Index Measure. 8, 9

UI User Interface. 1, 2, 6, 13

VDP Visible Difference Predictor. 9

VVA Valid Viewing Area. 1

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