Analysis of high dynamic range light field images in practical utilization contexts

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ABSTRACT

High Dynamic Range (HDR) imaging has proven its importance in numerous applications over the recent years. In the industry, there is an evident strive to further enhance the quality of the captured contents. Accordingly, legacy Low Dynamic Range (LDR) images are currently being reconstructed as HDR images due to their importance and usage in so many use case contexts. Analogous to conventional LDR and HDR images, the HDR reconstruction of light field images has also become relevant within the scientific community. Although the procedure of reconstruction is similar in several ways, the creation of HDR light field contents poses a significantly greater challenge and suffers from obstacles that are not present in case of the 2D counterpart. In this paper, we provide a context-dependent analysis of HDR light field imaging. The investigated use cases include, but are not limited to industrial prototyping, medical applications, control systems, digital signage, exhibitions of cultural heritage, education, cinematography and communication. The work takes into consideration global illumination and rendering challenges. The topics of real-time systems and services, cost-efficient practices, content availability, baseline-specific considerations, apparatus-specific optical limitations, user interaction and general plausibility are additionally emphasized in the analysis. The paper also provides a set of recommendations regarding the use-case-specific requirements of the investigated practical contexts.

Keywords: Light field, high dynamic range, image reconstruction, usage-specific requirements

1. INTRODUCTION

High Dynamic Range (HDR) imaging has proven its importance in numerous applications over the recent years. Currently, there is a strive towards enhancing the capabilities of the capture and display devices to accommodate the dynamic range of HDR images, which, in turn, adds realism to visualization by being close to the capabilities of the human visual system (HVS). In addition to providing a wider color gamut compared to conventional RGB, HDR images succeed at recording extra information which is not visible to the eye otherwise. This information can be of aid in multiple applications, including satellite imagery, physically-based rendering and medical visualization.

Whereas HDR adds realism to the visualized content, multi-autostereoscopic systems – including light field displays (LFDs) – immerse the users in a 3D experience without the need of additional viewing gears. This is achieved by interleaving columns – in the case of horizontal-only parallax (HOP) visualization – from multiple images of the scene with different angular perspectives, resulting in the parallax effect.[1] In 1992, Adelsen and Bergen[2] described LFs by means of a 7D plenoptic function, which was then reduced into a 4D function[3] in the case of free occluder space. Accordingly, an LF scene is achieved by rendering multiple 2D images. In the case

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of HOP visualization, the array of images is a 1D horizontal array; whereas for full-parallax (FP) imaging, a 2D array of images is rendered to create an LF scene.

Due to their added values, combining HDR and LF imaging shall create powerful, yet engaging results, and hence, can be integrated in many applications for enhanced performance levels. This, however, shall be rather challenging, as the limitations of both HDR and LF imaging need to be taken into account.

In this paper, we provide a comprehensive analysis of HDR LF imaging, in which we address the future use cases with the highest practical potentials. The investigated types of LF utilization include physically-based rendering, digital photography, image editing, cinematography, healthcare, cultural heritage, education, digital signage and telepresence.

The remainder of this paper is structured as follows: Section 2 discusses in detail the possible use cases for HDR LF imaging, in which each use case is separately addressed in an individual subsection. Section 3 concludes the paper and briefly reviews the future work.

2. USE CASES FOR HDR LF IMAGING

2.1 Physically-based rendering

Not only do we need to store the absolute radiometric values by the lighting and physically-based rendering programs, but also other quantities that are not visible to the human eye, as they could be used in further processing, reduction of accumulated errors, alpha and depth channels.[4] Since HDR adds more realism and is closer to the HVS, it is necessarily used in image-based lighting (IBL), especially for scenes with daylight. IBL describes the process of using real-world light images to illuminate real and synthetic scenes.[5] As an application to IBL by means of HDR images, the "Radiance" software was developed by Ward[6] as a physically-based rendering system. It is used in the context of architectural design as a means of predicting light levels and not-yet-built elements. Another attempt was carried out by Larson *et al.*,[7] where the authors created an operator that performs tone reproduction while maintaining visibility in HDR scenes.

Considering LF imaging, the same concept of IBL can be applied. In other words, a single HDR real-world light image is used for illuminating the scene. However, unlike the conventional methods, for a single LF scene, multiple images need to be rendered. This evidently takes more time, and thus, can be inefficient for real-time applications. Moreover, the baseline of the system needs to be considered, as wide-baseline systems may consider more than one image to be used in the IBL, since such systems span more space compared to narrow-baseline ones.

2.2 Digital photography

In order to create digital images with higher color fidelity, HDR digital photography was introduced. Although nowadays HDR cameras are already being introduced and novel ones are being developed, previous attempts for HDR capture included the use of exposure bracketing. The principle of such solution is that multiple LDR images with various exposures are captured and then combined together. The different exposures ensure having some pixels to be properly exposed unlike others. Due to the multi-capture method, static scenes are preferred, hence results are expected to be better when using a tripod or other types of stabilization in comparison to hand-held approaches.[8]

Generally speaking, HDR is incorporated in the current professional (video) cameras. In order to create a wide dynamic range, these cameras may either have the most sensitive light sensors or have the ability to combine multiple frames with various exposures. Most of these cameras have high-quality optics in order to capture as much light energy as possible, specifically in the dark areas.[9]

Capturing HDR images for LF displays depends on the baseline of the required system. For narrow-baseline systems, multiple attempts have been performed, including the focused plenoptic camera using a lenslet array, which was introduced in 2009.[10] Later, this camera was upgraded further for rich image capture.[11] In 2016, a two-camera hybrid system was proposed for HDR LF image capture by Wang *et al.*[12] Similar to the HDR image capture by means of multiple cameras, HDR LF image capture is achieved by using multiple plenoptic cameras.[13,14] Although these attempts rendered plausible results, they are expensive and custom-designed for specific applications. Moreover, they are specifically targeted for narrow-baseline LF systems. On the other hand, modifying hardware for wide-baseline systems is extremely expensive and infeasible. Accordingly, an alternative is to reconstruct HDR images from the captured LDR LF images by means of convolutional neural networks.[15]

2.3 Image editing

Nowadays, many applications support HDR image editing including – but not limited to – Photoshop since the CS2 release, Photogenics, Photomatix, Fotor, dpBestflow and Cinepaint. Certain image editing operations for LDR cannot be used for HDR, such as the addition and subtraction of pixels. Whereas the operations for LDR and HDR images are the same in terms of algorithm, running under or over range is possible when applying LDR operations to HDR images. Moreover, extreme colors, changes in contrast and white balancing for HDR images is different from that of LDR.[4] An example to the operations used in HDR (32-bpc) to LDR (8- or 16-bpc) image conversion by Photoshop includes either automatic operations (histogram equalization and highlight compression) or manual operations (local adaptation, edge glow, tone and detail, color, toning curve, exposure, and gamma adjustment).[16]

Since an LF scene is composed of multiple LF images, editing is more challenging. Depending on the case, editing for one image may need to be carried out for others as well to ensure consistency. In that case, editors for HDR LF imaging should include an option of either editing a single image – which may depend on the angular perspective – or editing all images in correspondence with the edited one at hand. Accordingly, keypoints between images need to be detected to further carry on the changes.

2.4 Cinematography

In order to use HDR in cinematography, it must be cost-efficiently fit for every digital cinema system. Compared to televisions, digital cinemas have relatively better image characteristics and increased sense of immersion for the audience, since they give filmmakers the ability to overcome the artistic limitations imposed by conventional displays. Accordingly, for the upcoming HDR generation of cinemas, they are required to provide a premium experience that exceeds that of HDR televisions. For the current conventional projectors, the vast majority has a contrast ratio of 6000:1. As for the Dolby Cinema, the same value is described as 1,000,000:1. For laser technologies, a wider gamut of colors is used.[17] Another attempt for using HDR in cinemas was performed by the *EclairColor* project in 2017, which aimed at deploying HDR for theaters around the world.[17] The project reported a contrast ratio of 8000:1.

For cinemas, projection technology has always been deployed by default. With the technological advancements in cinematography, modern digital projectors operate by emitting a uniform quantity of light onto a Spatial Light Modulator (SLM) to create the output images. These projectors use a subtractive-approach for creating colors. In other words, they block the light on a pixel-by-pixel basis to produce the required colors and shades in the image. Accordingly, by means of the subtractive approach, a pixel can never exceed the luminance of the Full-Screen White (FSW). Moreover, for most contents of the movie images, they have a Frame Average Light Level (FALL) of 10%, which means that almost 90% of the generated light is thrown away without reaching the screen. For HDR systems, the FALL shall include a smaller fragment of the peak luminance, resulting in more waste. In addition to the huge waste, due to the black level being linearly related to the FSW and the inability of SLMs to fully block the light, the contrast ratio is almost fixed. This is even worse in the case of HDR systems, as they inherently rely on high-contrasts images.

Hence, the main issue in HDR cinematography is the projection image-formation model. The following are the problems arising from this model in HDR, along with their unfeasible solutions:[18]

1. The illumination of a screen with high levels of light is demanding. A possible solution is to reach higher FSW by increasing the power, which requires higher energy consumption. It gets expensive exponentially, as light sources are not linearly scaled. Furthermore, it exerts very high capabilities on heat management, as well as system stability.

2. The dynamic range is the same even when the power is increased due to the light subtractive approach. A possible solution is to increase the contrast ratio capabilities of the SLM, as well as the black levels of the

projector by using better optical architectures. First of all, it leads to the reduction of power efficiency. Moreover, due to the projector screen being white or silver, light pollution from anywhere in the auditorium is added to the projected image, which, in turn, increases the effective black level of the projection system. Additionally, this solution also adds more expenses, and thus, it is economically unfeasible.

Ballestad *et al.*[18] proposed the idea of a light-steering projector in 2019. The work suggests to steer the light rather than to block it. In other words, the light that was blocked before in the dark regions is steered to increase the illumination of the bright regions instead. The authors displayed prototypes in the 2018 CinemaCon[18] – Advanced Imaging Society's HDR Summit and Hollywood studios. Even though light-steering projectors are capable of producing high peak luminances, they are limited by the light source supplies. Moreover, due to the light-steering techniques, these systems are adaptive in the sense that their peak luminance is affected by the image content statistics, where the peak luminance is inversely proportional to the FALL level of image. In addition to being affected by the image content and light source supplies, peak luminance is dependant on the maximum current that powers every diode. This steering technique affects the peak luminance, as well as the deep black levels within the image, depending on its content.

In addition to the problems raised by the projection techniques for HDR, additional challenges arise from the interaction between HDR and HVS, where these interactions are complicated and need further understanding. Among the difficulties concerned with these interactions are the complaints of the cinema artists on the software tools they work with, as they consider these tools to be dependant on basic vision science. Therefore, the film-making industry relies on manual alterations done by artists and technicians instead of automated methods, in order to match the appearance of the shot scene to that of the real world. Cyriac *et al.*[19] introduced the TM and ITM methods for the different processes in film making, including production, exhibition and post-production. Their algorithms are useful for cinema applications, since they are based on the vision models, where the parameters of the methods are fine-tuned by cinema professionals.

To sum up, it is essential for display manufacturers, as well as content creators to apply standardization defining the maximum characteristics achievable by the graded cinema content. If any display is incapable of inhibiting these standard characteristics, adaptive methods are then used to preserve both the required quality and the artistic goals.[18]

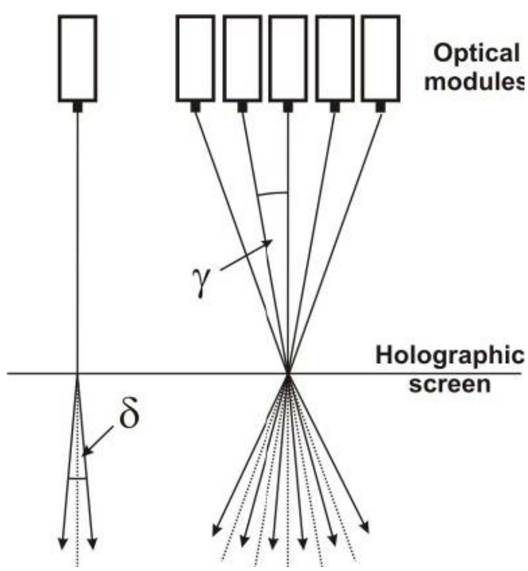

Figure 1. The HoloVizio setup[20]

Although 3D cinemas have gained popularity with more spectators, the usage of 3D gears degrades the overall experience. Accordingly, automultiscopic displays and LFDs are suitable for cinematography due to their ability to display multiple angular perspectives of the scene, resulting in a 3D sense of immersion without the need of additional viewing gears.[1,21] Since cinematography addresses multiple spectators at once, wide-baseline systems are the ones used. As an attempt for the usage of wide-baseline LFDs in cinematography, the HoloVizio C80 LFD[*] was implemented. Its huge size of 3 m × 1.8 m allows it for such utilization. Figure 1 shows the setup for the HoloVizio display composed of multiple projectors, where each of them creates the content visualized from a certain angular perspective.

Applying the concept of light-steering projectors to LFDs shall allow the spectators the experience of visualizing HDR contents in a cinema without the cumbersome nature of 3D glasses. In order to achieve such task, the light-steering concept has to be applied to each of the projectors used for the LFD.

2.5 Medical use cases

One of the main concerns in medical imaging is the set of possible limitations regarding the capabilities of the utilized display systems. An appropriate display allows for a reasonable trade-off between the diagnostic accuracy (i.e., the avoidance of false negatives and positives) and productivity (i.e., short interpretation times). Based on the research conducted by Reiner *et al.*,[22] the interpretation error rates for radiology include a range of 2% to 15% false positive readings, while false negatives occur more frequent in the range of 20% to 30%.

Since HDR allows more contrast levels and dynamic range compared to LDR, it is thus more efficient for diagnostic procedures, where medical images are supposed to convey information with the highest possible accuracy, in order to facilitate the disease detection task for clinicians. Medical imaging is affected by many factors, among which is image accuracy, bit depth, spatial resolution, dynamic range, viewing angle, arising artefacts (e.g., noise), and perceptual issues (e.g., contrast sensitivity and visual acuity). These factors need to be taken into account when designing displays for medical purposes. Whereas conventional displays have been effective in medical tasks, some medical applications that have fine details require displays with better dynamic range and higher luminance values. According to Ramponi *et al.*,[23] in order to display high-quality diagnostic images, at least three requirements must be met: (i) various levels provided by the detector (i.e., bit depth of the obtained datasets), (ii) complex mapping between the source data and the corresponding driving levels and (iii) visualization of source data and the corresponding driving levels as distinct luminance values on the display.

For conventional displays, HDR images undergo dynamic range compression or various techniques of tone mapping. However, doing this for medical imaging is not recommended since photometric distortions can occur to the processed data, rendering inaccurate information. Some attempts were done to display HDR data on conventional displays for medical purposes including the *window-and-level* method. On the other hand, long analysis time and the possibility of details distortion and/or loss occurs in the search phase of this method.[24] Another attempt took advantage of the eye-tracking techniques, where dynamic processing is being carried out on the display, such that the inspected area had its luminance and contrast optimized.[25] Currently, HDR displays have become available in the market among which is the HDR LCDs with 14 bits. These are used by radiologists and physicians, where medical image details are more subtle. While increasing the dynamic and luminance range, some of the image quality parameters are affected. Among which are the increased veiling glare, visual adaptation (done by retina) and optical crosstalk. Hence, more research needs to be considered for the mapping between the obtained datasets and the final visualizations. Due to the nonlinear behavior of HVS, nonlinear mapping needs to be carried out, taking into account the HVS when designing the map while adapting to the display's luminance range.[26]

3D imaging has proven its efficiency in many aspects of the medical field, including the diagnosis process, where a better understanding of the complex spatial structures is achieved, as well as better abnormality detection. An example to that is the increased detection rate achieved by stereoscopic devices in breast imaging. Moreover, 3D imaging has proven its importance to the manufacturing of the medical devices and treatments, as well as a better visualization of 3D ultrasound, leading to an increase in the visualization quality of the internal structures. Among the different important use cases of 3D imaging in the medical field is the minimally invasive surgery (MIS), resulting in a decrease in the surgical time while improving the surgical procedure accuracy.[27,28] Also, such displays have enabled the 3D visualization of the results of MRI and CT scans, which could further

[*] https://holografika.com/c80-glasses-free-3d-cinema/

enhance the neurosurgical applications.[29] Displaying HDR medical content on LFDs can be a breakthrough in medical imaging, resulting in an increased accuracy in diagnosis, detection and surgeries, while also resulting in a significant increase in the success rate of the different medical applications.

2.6 Cultural heritage

Cultural heritage – including archaeological sites – can be better visualized by means of computer graphics using digital surrogates. A digital surrogate allows for better insight and historical understanding by virtually representing real-world elements. Since visual appearance is a crucial factor for creating digital surrogates, light and illumination are key elements for better outputs. Accordingly, the more the light range is covered, the higher the rendering fidelity is, and thus, the more accurate the historical representation is. Unlike LDR, HDR imaging allows for a richer light acquisition in the real world, which can be later used in IBL for studying cultural heritage, thus, increasing the realism of the reproduced outputs. In addition to light acquisition, HDR provides visual documentation with more details when being zoomed in by reducing the clipping of the subsurface information.[30,31]

As a means of visualizing the digital surrogates, LFDs provide an excellent choice, as they allow spectators and researchers to navigate through the 3D scene. In addition to visualizing the contents of cultural heritage, LFDs are best deployed in museums and galleries for viewing exhibitions. Since visitors are highly mobile and can walk freely in museums, using LFDs present such contents better, since they provide the correct angular perspectives from any viewing position within the valid viewing area.[32] Accordingly, visualizing HDR contents on LFDs shall help in studying and researching cultural heritage with easy navigation and manipulation through the 3D scene. Moreover, deploying HDR LFDs in exhibitions shall increase the engagement of visitors due to the combination of vivid colors and general 3D immersion. This is particularly applicable to wide-baseline LFDs.

2.7 Education

Among the various fields in which HDR can be used as an educational tool is architectural education. Based on the work of Debevec,[33] rendering synthetic objects in real-world scenes has become possible, hence, bridging the gap between the physical sites and digital designs. Accordingly, IBL has enabled HDR to become a useful, practical tool for architecture education, where the technical aspects of lights are taught.[34] This allows for a complete design education – according to Watson[35] – where the light is taught in connection to the site and the environment, allowing easier experimentation.

Due to its ability to simulate 3D scenes, LF can be used for educational and training purposes, where learners can understand the internal structures of complex devices (e.g., gearboxes and engines) or the human body.[36] Hence, it is better suited for higher levels of education, as well as specialized training.[32] Accordingly, visualizing HDR LF content can be highly advantageous in the field of education, as it shall enhance the learning curve due to engaging the students, while creating content with clear details and colors. Both narrow- and wide-baseline LFDs can be used for different educational purposes. Whereas the wide-baseline systems offer visualization to multiple students at once, narrow-baseline systems can be used in single-user scenarios for a more focused and personalized learning experience.

2.8 Digital signage

With the fast-moving technological developments, the customers of the current era have become sophisticated media users with growing expectations towards visualization quality. Accordingly, HDR digital signage is becoming a necessity, where high-quality engaging content incorporating a wide range of vivid colors while having a natural effect is expected. Accordingly, LED displays visualizing HDR contents have now been developed and used in the market, where they provide the best viewing experience, especially when compared to LCDs.[37,38]

Among the different attempts for HDR digital signage is the Samsung QMR series[†], which uses ultra-high definition (UHD) up-scaling technology for visualizing LDR contents, creating "life-like" images. In addition to the up-scaling, the QMR/QMT series enables good visual experience from all angles by means of non-glare

[†] https://displaysolutions.samsung.com/pdf/brochure/5257/Smart_Signage_QMR_QMT_Brochure_210909_WEB.pdf

panels, as well as performing noise reduction while using dynamic color crystals for creating a high dynamic range of colors (almost one billion color shades). For easier usage and mount, this series features slim design. Other attempts included Sony with its new BRAVIA 4K HDR professional displays‡ that could be used to present HDR contents in the field of digital signage, and Vestal§ and LG¶ digital signage with their different series for visualizing HDR content.

Introducing LFDs for digital signage while creating HDR contents shall greatly improve the market due to their ability to grab the users' attention with their vivid colors, as well as the glasses-free 3D visualization. The added 3D effect shall allow spectators to view the advertised contents from multiple perspectives, adding realism and increasing the plausible outcomes from the utilization of digital signage, while engaging the users and consumers. For digital signage, it is preferable to use wide-baseline LFDs to target numerous consumers at once.

2.9 Telepresence

In recent times and especially since the emergence of the COVID-19 pandemic, online meetings and video conferences have become more of a necessity. This emphasizes the importance of creating high-quality sounds and visuals for calls. As a solution to this issue, 3D telepresence systems are being developed for real-time audiovisual connection. In addition to being used in communication, telepresence can be used to immerse users in remote sites with high degrees of realism, which can be further used in virtual reality (VR).[39] Since outdoor scenes have a high dynamic range of luminance, where the sun is almost 2^{17} times brighter compared to the dark areas in clouds,[40] representing those scenes in telepresence by means of LDR imaging results in poor quality outputs. Hence, HDR imaging is deployed[39] by means of exposure bracketing, where multiple LDR images of the scene are captured with different exposures and merged together to create HDR contents.[41]

Utilizing LFDs in remote meetings can greatly enhance the visual experience, where LFDs with the same size of the individuals can be used to add realism and create a higher sense of presence, as well as engaging environments.[36] As an attempt for telepresencing by means of LFDs, the HoloVizio 1080T[42] provided by Holografika – having the dimensions of 180 cm × 100 cm and an FOV of 180° – creates a full-size portrait. Moreover, the LightBee[43] implementation addresses the same telepresence problem by displaying only the head of the user. In both telepresence utilization cases, using HDR along with LFDs can create more engaging experiences in the audiovisual calls, as well as immersing the users in remote sites with a higher sense of realism and 3D immersion, close to real-life experiences.

3. CONCLUSION AND FUTURE WORK

With the technological evolution, two new concepts have emerged in the last century: HDR and LF imaging. With HDR, users are able to view contents with more range of colors compared to conventional RGB imaging, producing vivid results, close to the capabilities of the HVS. On the other hand, LF visualization provides the ability to view 3D contents without the need of additional viewing gears, thus, engaging the users by immersing them in the created scenes. Combining both technologies, HDR LF imaging shall create powerful results that could be used in multiple applications.

In this paper, we have discussed each of the possible use cases of HDR LF imaging. Further research is needed while taking into account each use case individually, since each of the latter considers some aspects to be more important compared to others. Moreover, limitations of both HDR and LF imaging needs to be taken into account for better design outputs.

‡https://cdn.cnetcontent.com/5f/8a/5f8a2146-0a42-477b-9d4d-dea498205aea.pdf

§www.vestelvisualsolutions.com

¶https://www.lgbusiness.it/wp-content/uploads/2020/07/Catalogo-LG-Signage.pdf

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