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The key performance indicators of projection-based light field visualization

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ABSTRACT

At the time of writing this paper, light field visualization has entered the professional environments in the industry and has also become commercially available. It is not yet present on the consumer market, however, and its widespread emergence is expected in the following decade, with affordable end user devices and a vast variety of applications and contents. The successful integration of this technology into people's everyday lives essentially depends on the visualization quality, which is achieved through excellence in terms of the key performance indicators of the display system and the content it visualizes. In this paper, the key performance indicators of light field visualization for both display and content are reviewed. Beyond providing a comprehensive review of the vital parameters of visualization quality, this paper discusses the ongoing and future relevant research efforts, demonstrates the practical uses of the technology, highlights certain dependencies between the indicators, and addresses issues of perceived quality with regard to the lack of compliance with the requirements and visual thresholds.

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1. Introduction

The concept of light field first emerged over a hundred years ago, through the work of the French physicist Gabriel Lippmann on integral imaging [1]. The origin of this technique's name is Lippmann's term 'photographie intégrale,' which can be directly translated as 'complete photography' or interpreted as 'complete imaging.' Its motivation was and still is the incomplete nature of 2D visual representation; our 3D reality simply cannot be fully embodied in a flat 2D image. In recent years, multiple solutions regarding 3D visualization established a presence on the consumer market, most of which were fundamentally dependent on viewing devices (special glasses and headgears). Not only do such equipment limit the number of simultaneous viewers of a given content; they also pose numerous inconveniences and issues. Light field displays offer a glasses-free 3D experience as no such equipment is required; therefore, any number of viewers can simultaneously observe the content, without the inherent problems of the other technologies.

This of course does not mean that any light field content visualized on any light field display is de facto superior in visual experience to any other 3D technology. There is a long list of parameters that directly affect the

quality of light field visualization in terms of both display and content. They are key performance indicators (KPIs) as they define the objectively and subjectively measurable visual performance, and any of them with insufficient characteristics may severely degrade the overall quality of light field visualization.

In this paper, the KPIs of light field visualization are systematically reviewed. The properties of displays and contents are separately presented in detail, but their interdependencies are also taken into account. For each parameter, the state-of-the-art scientific results are discussed, and based on the collective expertise of the authors, use-case-aware recommendations for display manufacturers and content providers are made. As an additional contribution, the paper also discusses the future research efforts on the capabilities that have yet to be available for the present high-end systems, including some of the authors' own ongoing innovations.

The remainder of this paper is structured as follows. Section 2 describes the properties and capabilities of light field displays that can affect the perceived quality. These parameters are separately introduced for the physical setup of such systems and for light field projection. Section 3 presents the detailed parameters of the

visualized content, bearing in mind the potential future use cases of this technology. Section 4 discusses the ongoing and upcoming research efforts on important technological features that shall contribute to visualization quality but are yet to be implemented. Finally, the paper is concluded in section 5.

2. Display parameters

In this section, the parameters of display systems that are relevant to light field visualization quality are reviewed, their contributions to the visual performance are addressed, how they affect one another is analyzed, how the insufficient properties are manifested in practice is explained in detail, recommendations for achieving visual excellence are provided, and the state-of-the-art related work is introduced. The scope of this paper does not include lenticular displays like the Alioscopy 3D display [2] and near-eye light field displays, such as the ones presented by Lanman et al. [3] and Hansen et al. [4].

Light field displays often appear in the scientific literature as super multi-view (SMV) displays. There are two fundamental differences between multi-view displays and SMV displays. The first one is regarding the angular resolution of the physical setup, which will be elaborated later in this section. While multi-view displays typically accommodate views in the order of 10, the corresponding value for the SMV display is in the order of 100, or even 1000. The other major difference concerns projection. Multi-view displays can be viewed from very specific positions, and the exact same visualization (how the content is observed) can be seen from all positions, regardless of the viewing angle with respect to the orientation of the screen. In the case of SMV displays, there is no content repetition as the users are not limited to certain positions. Therefore, if a multi-view display can show contents with a high angular density and the multiple viewing positions are replaced with a single area in which visualization is virtually continuous, then it can be called an SMV or light field display.

A light field display can be either a front projection system or a back projection system. Front projection systems have projectors on the same side of the screen as the observer, and as light rays are basically reflected from the screen to the eyes of the observer, these systems are also known as reflective displays. Back projection systems, on the other hand, evidently have projectors at the other side of the screen and are therefore transmissive displays. Regardless of the location of the projectors, the display parameters can be categorized into those that are derived from the physical setup of the system and those that are defined by projection.

2.1. Physical setup

2.1.1. Screen dimensions

One may think that discussing the physical dimensions of the screen is trivial and unnecessary, but these parameters affect the visual performance of the system much more than just how big the screen that the observer is looking at is. The size of the screen fundamentally determines most system requirements; bigger screens demand higher capabilities. One must note that the system scales up together with the screen, and it may also directly influence other parameters, such as the physical depth. As an example, for reflective systems, having the same screen width but a different screen curvature (curved shape of the screen) results in a different field of view (FOV). This will be explained in detail later in this paper, together with other attributes that have an effect on the FOV. For both the back and front projection systems, the spatial requirements can be prohibitive for deployment and practical use; having a bigger screen also scales up the physical size of the projection subsystem.

In practice, the screen of light field displays may vary much in terms of the physical dimensions; it can be said that they appear in various shapes and sizes, and they actually do. To the best of the authors' knowledge, the smallest light field display that has been used for research purposes was the one that appeared in the work of Adhikarla et al. [5], with an 8.6-inch screen. The largest systems were upscaled designs of a light field cinema [6], proposed by Kara et al. [7]. Different variations appeared in the publication in 450-, 540-, and 630-inch sizes. Among the large-scale implementations of the multi-view and SMV technologies today is a system with a 100-inch screen designed by Lee et al. [8] and a 200-inch display worked on by Inoue et al. [9], similar to that designed by Kawakita et al. [10]. At the time of writing this paper, the largest commercially available light field display was the HoloVizio C80 cinema system [6], with a 140-inch display.

2.1.2. Spatial resolution

The spatial resolution of light field displays is often labeled as the 2D-equivalent resolution of the system. It is a general statement in the literature that the concept of pixels does not apply to such systems as light rays hit irregular positions on the screen. In a way, we can indeed talk about pixels in the context of light field displays, however, it most certainly does not apply to them in the way we know it for 2D displays. Due to this aforementioned irregular nature of light ray propagation, the grid of pixels is far from being uniform. Furthermore, even though pixels can be identified, the position, color, and intensity of a given pixel is direction-selective, which means that the

perception of the pixel depends on where one observes it from.

An insufficient spatial resolution for light field displays does not result in the same blockiness apparent for the conventional 2D displays. Instead, visualization is affected by blur. It is important to note that the blur that applies to such displays is not uniform across the screen. The amount of perceived blur is determined by pixel density, measured in pixels per inch (ppi) or pixels per centimeter (ppcm), which also depends on the screen size. The typical values of ppi for light field displays are between 10 and 50. For example, due to the large screen of the C80, it has a ppi of only 10.8 while the smaller screens of the HoloVizio 722RC [11] and the 80WLT [12] have 22.6 and 47.2 ppi values, respectively.

The smallest spatial resolution that has been applied thus far to a fully implemented system was 320×240 , with a screen size of 144×81 mm. The common values in practice include 1024×768 [6] and 1280×720 [11]. The highest spatial resolution of a light field display at the time of writing this paper was 1920×1080 , which applies to an experimental system of Holografika that is not yet commercially available.

Kovács et al. [13,14] measured the spatial resolution values of light field displays. The proposed method of measuring the display capabilities uses sinusoidal patterns with increasing frequency, which are displayed on the screen and are captured and analyzed in the frequency domain. The procedure is fully automatic for the spatial resolution, and does not require any camera movement, in contrast to the angular resolution, which was also addressed by the authors' research. Recommendations regarding the general techniques of such measurements are provided by International Display Measurement Standard (IDMS).¹ IDMS also covers measurements related to several other parameters, such as the angular resolution and FOV.

2.1.3. Angular resolution

The angular or angle-dependent nature of light field displays means that a different view of the visualized content will be seen from a different angle of observation. This visual phenomenon is analogous to what can be seen in the real world as light field displays aim to provide the parallax effect. This means that the portions of the visualized content that are farther away from the observer change the perceived position more slowly than those closer to the observer do. This effect applied to the horizontal axis is known as the horizontal parallax, and vertical change relies on the vertical parallax. The currently available systems are horizontal-parallax-only (HPO) light field displays, and the future development is converging towards full-parallax (FP) displays.

It is important to note that the parallax effect provided by such displays is continuous in the entire FOV while multi-view displays show angularly repeating contents that are observable only from certain positions, known as 'sweet spots.'

The angular resolution is technically the resolution of angular change, which applies only to the horizontal axis in the case of HPO displays. To be more precise in defining this term, it is the minimal angle of change that rays can reproduce with respect to a single point on the screen [15]. Figure 1 illustrates the definitions of angular resolution. γ is the common understanding of the mechanical angular resolution, which is the angle between horizontally adjacent light rays targeting a given point on the holographic screen, and δ is the corresponding angle for the distinct light rays leaving the surface of the screen. These two angles are not equivalent as δ depends on the scattering characteristics of the screen. In practice, although both values are either calculated or measured, it is γ that describes the angular resolution of the display system. The calibration of δ is used to improve the homogeneity of light field visualization. For visually efficient light field displays, the value of γ is close to δ , but δ should always be slightly greater. If δ is much greater than γ , however, the angular resolution is jeopardized as the extensive scattering mixes up the rays that were originally in the correct horizontal order before reaching the screen.

Generally speaking, the angular resolution defines the smoothness of the parallax effect. This is by definition the smoothest in the plane of the screen. Therefore, the more a given content comes out of the screen, the higher the angular resolution required to sufficiently support its angular smoothness. Furthermore, the perceived angular resolution depends on the observation distance measured from the plane of the screen; thus, it also determines the viewing distance supported by the display.

Therefore, a system with a low angular resolution may not be able to properly display a content with greater depth, and the observers viewing the display from a certain distance may not even experience the 3D nature of light field visualization. Building a system with an insufficient angular resolution may also result in artifacts and visual phenomena like the crosstalk effect, which means that the adjacent views overlap each other in a semi-transparent manner, and the total lack of parallax smoothness can create sudden jumps between the given views. Furthermore, a δ that is much greater than γ also results in the crosstalk effect due to the previously mentioned reason.

The lowest angular resolution in practice thus far was 2.25 degrees, which belonged to an experimental system of Holografika. The commercially available HoloVizio

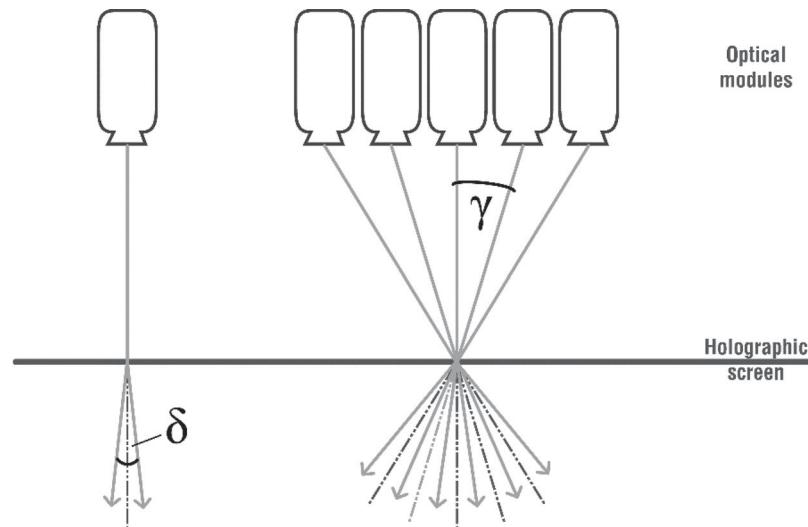


Figure 1. Illustrations of angular resolution definitions.

80WLT has an angular resolution of 1.5 degrees, and the highest angular resolution that is currently in use is 0.5 degrees, applied to the C80.

2.1.4. Depth budget

The depth budget is a distance vector perpendicular to the plane of the screen, and measures the extent to which the content can come out from this plane. It is more or less symmetric, which means that this distance is approximately the same for the positive (towards the observer) and the negative (away from the observer) direction. It is called a ‘budget’ as the content does not necessarily need to fully use it. The depth budget directly scales up with the angular resolution and the size of the pixels on the screen; as such, for a reflective screen, it is also determined by the dimensions of the screen itself.

There is a linear relationship between these parameters. This means that if the angular resolution is doubled while the pixel size remains the same, the depth budget becomes twice as big. The same is true if the pixel size is doubled while the value of the angular resolution is unchanged. The only condition that must apply for this linear relationship to be true is that the pixel size needs to be significantly smaller (at least one order) than the projector period. The projector period is technically the physical distance between the adjacent projectors in the array (see Figure 1). If this condition is not fulfilled by the display system, the depth budget will increase faster than linearly. Although this may result in a fairly large depth budget, it also means that it will become challenging to perceptually distinguish the different depth levels of visualization.

The smallest depth budget in practice thus far was credited to the 8.6-inch screen of the display used in the

work of Adhikarla et al. [5], which was a mere 10 cm. To the best of the authors’ knowledge, the greatest depth budget achieved thus far in the case of a real light field display was 1.5 m [6]. When compared to the size of the screen, a remarkable depth budget was 1 m, which was achieved for the screen size of a regular PC monitor (unpublished work of Holografika). The greatest depth budget presented thus far in publications was 12.5 m [7], which has not yet been implemented.

2.2. Projection

2.2.1. Field of view

FOV is an angle that determines the area in which light field visualization takes places. While near-eye 3D technologies approach FOV from the perspective of the observer, FOV in the case of light field displays applies to the display itself. One of the greatest advantages of such systems compared to sweet-spot-based displays is that they can utilize the entire FOV to visualize a given content, with a virtually continuous horizontal motion parallax.

In the current literature, FOV refers to the horizontal angle of HPO systems. For the future FP displays, FOV can also encompass a vertical component. Even though FOV appears to have already been well defined, however, it has two co-existing definitions in practice, which are in fact both correct yet provide different values. Figure 2 shows these two FOV definitions. The one on the left defines FOV as the angle of the valid viewing area (VVA) while the one on the right measures FOV directly from the screen. The VVA takes the depth budget into consideration; the bigger the depth budget is, the farther the VVA is from the screen. If an observer comes closer to

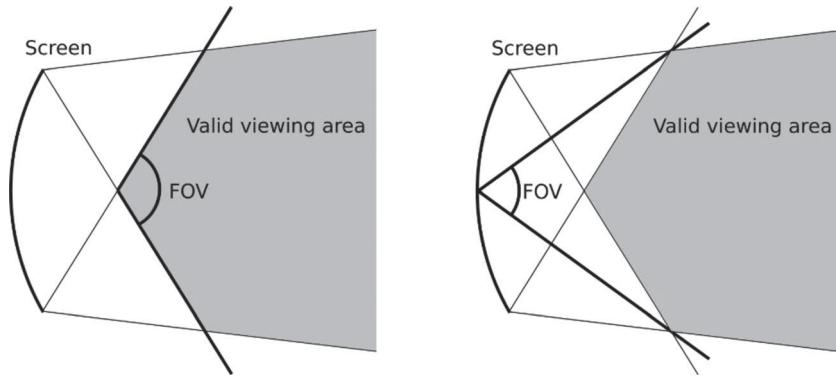


Figure 2. Illustrations of FOV definitions.

the screen than the distance allowed by the VVA, the observer may perceive an invalid, broken light field due to the missing visual information. Furthermore, front projection systems create their own restriction for the shortest valid viewing distance because having an observer occlude with the light rays that are cast onto the screen also results in missing visual information (in the form of a dark shadow). Finally, it must be added here that the screen dimensions also affect the VVA, as shown in Figure 2.

Again, both FOV definitions are correct, but it will be observed that the one measured at the VVA is always at least as big as the one measured at the screen. Therefore, display manufacturers and constructors of prototypes can indeed be encouraged to use the first one so that they can use a bigger number in the system specifications.

In the scientific literature, FOV and VVA are usually treated as synonyms or as equivalent terms. VVA is sometimes also written as a valid FOV because it is a portion of the area defined by the FOV that enables the valid perception of visualization.

Having a sufficiently large FOV is required for multiple reasons. If only a single observer is considered, the shape and size of the VVA determine the positions (and orientations) from which the content can be viewed, and also set the boundaries for observer movement. For the case of multiple observers, a bigger FOV also means the accommodation of more simultaneous observers. Lastly but evidently, a greater FOV enables more viewing angles for the given content.

The smallest FOV that has been utilized thus far for research and development purposes was the windshield head-up display (HUD) of an experimental vehicular system. As the display was directly designed for only the driver, the distance of observation and the horizontal deviation of the head position were highly constrained. Therefore, an FOV of approximately 30 degrees was sufficient for the given application. This value was measured

at the VVA vertex, and the corresponding value at the screen itself was only 20 degrees. Ni et al. [16] proposed a 360-degree large-scale multi-projection light field display. In this system, 360 optical modules project images onto a cylindrical diffusion screen with a 1.8 m height and a 3 m diameter. In between these extremes, the FOV of the C80 is 45 degrees, that of the HV722RC is 70 degrees, and that of the 80WLT is 180 degrees.

2.2.2. Overall resolution

The overall resolution is the number of individual pixels detectable within the FOV. This value can differ significantly from the number of pixels projected from the optical modules due to the optical loss in the display frame. The optical efficiency of the display is characterized by the ratio of the overall resolution to the total projected resolution.

With regard to visualization quality, the overall resolution should be as near to the total projected resolution as possible. With every light ray lost due to the difference between these two, the visualization quality is actually diminished as fewer rays compose the same light field.

In practice, the optical efficiency is around 80–90%. This means that roughly 10–20% of the emitted rays do not contribute to light field visualization. Well-optimized systems tend to reach 95–96% optical efficiency, but it does not go beyond that, although even 100% is theoretically possible. The reason that 100% optical efficiency cannot be achieved in practice is that other parameters must also be considered. For instance, in the case of a wider FOV, due to the skewed projection to achieve it, a certain amount of light rays is lost.

2.2.3. Brightness

Even though the properties of the projection subsystem are discussed in this subsection, the brightness is measured at the screen itself and not at the projectors. The brightness value of a system is measured by projecting

a completely white image onto the screen. While the entire technological sector refers to the phenomenon at hand as brightness, what is actually being dealt with is the photometric measure of luminous intensity per unit area.

The first commercial light field display, the HoloVizio 128WLD, had a brightness value of 20 cd/m^2 . This value is more applicable to cinematic scenarios as the proper perception of visualization requires more or less dark surroundings (approximately 20 lx). Any value above 1000 cd/m^2 is suitable for general system deployment in most scenarios. For example, the C80, the 640RC, and the previously mentioned automotive HUD have brightness values of around 1500 cd/m^2 .

If the brightness is insufficient compared to the environmental lighting conditions, visualization cannot be properly perceived. Comparably low brightness directly affects the perceived contrast value of the display as the environmental light degrades the perception of the darker segments of the visualized content.

With the state-of-the-art projectors and even most of the regular projectors available at the time of writing this paper, brightness typically does not pose an issue when designing light field display systems. For example, if a large 120-inch screen with 100 projectors and an FOV of 45 degrees is considered when 500-lumen projectors are used, then visualization is suitable for any given environment and use case.

2.2.4. Contrast

The contrast of a light field display is directly determined by the contrast of the projection subsystem. In this context, contrast is thus the ratio of light rays with the lowest and highest possible intensities.

The lowest contrast in practice thus far was 100:1, which was applied to the very first light field displays. Most of the displays available today typically have between 500:1 and 2000:1 contrast.

If the contrast of a light field display is insufficient, the visualization details are lost as only the differences between the bright and dark portions of the content can be properly perceived. Contrast largely depends on the use case and the content itself. For example, if the light field HUD of a vehicle is considered, the perceived contrast will be low due to the background of visualization, but there is still a high system contrast requirement. As most advertisements apply high-contrast contents, using a light field for advertising comes with rather low system contrast requirements and focuses more on brightness. On the other hand, in a medical application of the light field technology, any loss from the necessary contrast levels can result in diagnostic inaccuracy.

2.2.5. Refresh rate

The refresh rate of light field visualization is basically analogous to that of 2D technologies. Therefore, the quality requirements related to the refresh rate can be considered the same. 60 Hz can be achieved by the projection subsystem, but this is a challenge with regard to the frame rate of certain use case scenarios and content types. This will be discussed in detail later in this paper.

2.2.6. Colorspace

The color space considerations in the context of visualization quality for the projector array of a light field display are mostly equivalent to those for the conventional 2D projection. The only aspect here that needs special attention is the color calibration of the projectors. This is typically performed via software.

Without proper calibration, especially in the case of a large array with numerous projectors, the projectors do not emit light rays with a perfectly identical color space. This can easily lead to incorrect content colors and color mismatches, and even worse from the user's perspective, certain areas of the projection (commonly vertical areas, but it depends on the construction of the array) can stand out from the rest of the content, degrading the general user experience and the natural feel of glasses-free 3D visualization.

3. Content parameters

Light field displays may visualize all sorts of content, like static 3D models, light field videos (including real-time transmission), and interactive applications (e.g. games). In this section, the content parameters are clustered into common parameters, which apply to any given content, and content-specific parameters.

3.1. Common parameters

3.1.1. Resolution

Content resolution can be approached based on the content type. In a still image or video content captured and stored as a series of 2D images, the 2D resolution of these images is the spatial resolution, and the ratio of the number of images to the FOV is the angular resolution. The HPO content is basically a 1D array of images, and the FP content can be imagined as a 2D matrix in this type of representation. In practice, these images are converted by the converter at the input side of the system, turning a discrete set of images into a continuous light field, by assigning the appropriate light rays to the optical modules.

If the content is directly rendered from a 3D mesh, the content resolution will have a different definition. Methods of rasterization and ray tracing are used, and

even though they differ much in terms of implementation, they both create the final 3D content with the display parameters. This means that if one wishes to ray-trace a given scene, the output will match the display's spatial and angular resolutions. The primary difference in usage is that rasterization is more suitable than ray tracing for real-time contents (e.g. light field gaming) due to the former's lower computational requirements.

In the case of converted contents, if the resolution values are insufficient for the given use case scenario and display, then the degradations are analogous to what applies to the display itself. Therefore, a low spatial resolution results in a blur that is not uniform across the screen, and a low angular resolution comes with a loss in the smoothness of the parallax effect and with the previously discussed visual phenomena, such as the crosstalk effect.

The works of Kara et al. address the spatial [17] and angular [18] resolutions, and investigate their interdependence [19]. The authors applied degradations to converted still image contents through reductions in the spatial and angular resolutions, and found that the visual phenomena induced by the disturbed parallax smoothness can be lessened by the blur caused by a low spatial resolution. The research on the spatial and angular resolutions was also extended to the context of the light field video [20]. The results for both the still image and the video content highlight the fact that while reductions in the spatial resolution may be tolerable, the subjective acceptance of a 1 degree angular resolution is quite questionable. This is in alignment with the work of Tamboli et al. [21], which discusses the need for light field research contents with a higher angular resolution and provides a database of camera-captured models with a 0.5 degree content angular resolution.

3.1.2. Frustum

Frustum in the context of light field visualization is a geometrical portion of a 3D space defined by the cutting planes, and thus describes the space in which the content resides. The cutting planes in the front and back define the depth of the content, and the ones on the sides are aligned with the properties of the projector array. The primary properties here are the projection aspect and the horizontal projection angle. This implies that the best visualization can be achieved if the content generation takes into account the display for which the content is created.

If the depth value of the frustum is too small (i.e. the frustum is not deep enough), then the content is inherently limited in terms of the depth of its visualization. If the frustum, however, is too deep in contrast to the depth budget of the display, then visualization suffers multiple issues. First of all, the portions of the content that

go beyond the limits of the positive and negative depth budgets cannot be properly addressed by the light rays of the projector array. This results in invalid light field data, which also affects the rest of the visualization.

If the frustum is too narrow compared to what the projection would demand, then either the sides of the visualization become invalid or the content needs to be stretched and cropped, resulting in the loss of visual data and in skewed proportions. If the frustum is too wide, it is less problematic because the common solution to this is simply cropping the data. Having a frustum with inappropriate height parameters in HPO visualization is analogous to these issues.

3.1.3. Scalability

Scalability is a property that characterizes the upscaling and downscaling procedures for various content types. In the case of static scenes and videos, where the source content is a series of 2D images, the concept of scalability is similar to that for the 2D technologies. Basically, the resolution values determine the extent to which a given content can be upscaled for a specific display. For instance, if the angular resolution of the content is much lower than what the display supports, then the conversion procedure may create major inaccuracies in visualization due to the high extent of interpolation. The word 'may' is key here as displaying a high-angular-resolution content on a display that has an even higher angular resolution (in fact, a much higher angular resolution) will not necessarily result in the degradation of the subjectively perceived visual quality. Objective quality metrics, however, may still measure the effect.

Projection-based light field displays always interpolate the source content during conversion, even if the properties of the content perfectly match the capabilities of the display. To see how this applies to downscaling procedures, an example is in order. If there are two contents, one with a 0.5 degree angular resolution and another with 0.33 degrees, and one wishes to convert both of them for a display with a 0.5 degree angular resolution, then the second one is expected to have a better perceived quality. This is because both contents get interpolated, but the second one has a higher view density to begin with. Of course, as these values get higher, the perceived differences get smaller. Furthermore, the gain in visual quality will also decrease as the distance between the angular resolution of the content and the display increases. In a display with a 0.5 degree angular resolution, if the contents are converted with 0.3, 0.2, and 0.1 degree angular resolutions, then the perceived difference between the first and second converted contents will definitely be smaller than that between the second and third converted contents. In fact, it is arguable if there would be any perceived

difference at all between the second and third converted contents.

Point clouds are slightly different in the context of scalability. Basically, the loss in visual quality is replaced here by the so-called ‘holes’ in the content. This means that if the point cloud content is upscaled to an extent beyond what it could support, then the distances between the adjacent points will become too great, and the continuity of the visualized content will be disturbed. For 2D view arrays, scalability is based on the resolution values, and for point clouds, it is approached by the distance between the points. To be more precise, the scalability threshold can be determined by the distance of two adjacent points with the greatest distance from all the adjacent point pairs in the model or the scene, because that pair will be the most vulnerable to upscaling (i.e. it will be the first to have a hole in between the projected points).

3.1.4. Color space

The color space of light field visualization is analogous to that of the 2D visualization technologies. The only main difference is within the color space of the projection subsystem, which has been explained in detail earlier; the color space of the content has no special consideration with regard to visual quality.

3.2. Content-specific parameters

3.2.1. Frame rate

The frame rate does not apply to several types of light field content (e.g. static models); it applies only to light field videos and interactive applications. The video frame rate is completely analogous to its 2D counterpart. As for interactive applications, it depends on the computational requirements of the content and on the computational capacities of the system.

Displaying a content with a high frame rate can be challenging for several reasons. First, it requires more data to be stored and transmitted. Second, even though the GPUs of the system may have a solidly high frame rate on their outputs, this does not guarantee a sufficiently high final frame rate. This is because the different GPUs may have different workloads due to the diversity of computational requirements based on the content itself; the content may very well be simple from a specific direction while it may be quite complex from another direction. Furthermore, these GPU outputs need to be synchronized, and thus, the slowest one may become a bottleneck of the entire visualization process.

3.2.2. Compression

A light field content does not necessarily need to be compressed. Compression is of course desirable, however, as

a light field content usually has a tremendous amount of data. If one wishes to store and transmit such data, especially in real time, then the smaller the data (file size or data rate) is, the better. There are many applications of this technology, however, that do not involve the processes of storage and transmission. These are typically the interactive applications, where the visualized data is a collection of rendered 3D meshes.

If one does compress, such as for static models and videos, then compression can happen in two fundamental ways. One is by using the conventional compression for the 1D and 2D view sets, where the views are separately compressed. Real light field compression relies on the redundancy between these views [22]. Although wide-baseline light field displays and the associated contents are primarily focused on in this paper, it is necessary to review the compression methods used for narrow-baseline lenslet-based light fields as both techniques can exploit inter- and intra-view redundancy for light field compression.

An example of the compression of a light field acquired by multiple cameras is the work by Tamboli et al. [23], where camera images were separately compressed using the JPEG, JPEG2000, and WebP compression methods. Similarly, the array of lenslet images captured using plenoptic cameras – considered a single image – was compressed using intra-coding methods [22,24].

The light field compression methods that rely on inter- and intra-view redundancy have been shown to be better in terms of various objective quality metrics, especially for high compression ratios [22]. For multi-camera sequences, the multi-view extension of High-Efficiency Video Coding (HEVC) has been used to exploit spatial, angular (inter-view), and temporal redundancy [25,26]. Similarly, the multi-view compression methods targeted towards lenslet images arrange contents as pseudo-temporal sequences [27]. The compression of a light field using point cloud codecs has also been proposed in the literature. For example, the work of Zhang et al. [28] maps the multi-view images to a point cloud and jointly compresses the geometry and the view-dependent colors.

Again, it must be noted that the size of the light field data after conversion is not dependent on the compression of the source content. On one hand, compression may negatively affect the quality of visualization, but on the other hand, it may boost the performances of applications relying on data transmission.

3.2.3. Render type

The visualized light field content can be a converted image set, or if there is a 3D mesh, a rasterized or ray-traced content will be seen. Light field images and videos that are captured by a real or virtual camera array are

typically the first case. Static scenes and videos can also be rendered by using methods of ray tracing for virtual content generation. Interactive contents like games and applications requiring user input are normally represented by 3D meshes. These meshes are either rasterized or ray-traced before their visualization on the screen of the light field display. Rasterization is computationally less expensive and faster; as such, it is the most common visualization method for such contents. Ray tracing is also possible, as demonstrated by the work of Doronin et al. [29].

The methods of rasterization and ray tracing are analogous to the conventional 2D visualization; ray tracing enables more life-like visuals compared to rasterization as it traces light rays through the given 3D scene. These operations, however, are not only content-specific but are also display-specific, without any intermediate process. The output that they provide directly matches the display parameters. In contrast, conversion creates intermediate visual data, which is then interpolated for the projector array.

4. Discussion on the current and future research efforts

This section discusses the quality indicators and features of light field visualization that have not yet been fully implemented and that are to be integrated into such systems in the future.

4.1. Super resolution

Super resolution in the general context of light field technology is often understood as a reconstruction method for increasing the spatial resolution at the capture side [30]. It has a great potential for enhancing the quality of the reconstructed content to be displayed. In the context of light field displays, however, super resolution has a different meaning.

When the aforementioned technical term is applied to display systems, it refers to extremely high resolution capabilities. By resolution, the angular component is largely meant, but the spatial resolution is also a vital part of it. The core concept of super resolution is that the achieved display resolution – and of course the visualized content – is so high that the human eye can focus on different portions of the content. Such a display may also be labeled as an accommodative display because the display presents a true focal depth cue, inducing a correct accommodation response to the eye.

Early in this paper, it was elaborated that one of the reasons that SMV displays are ‘super’ is the high angular resolution of the physical setup. Following this logic,

it is possible that in the future, the continuing increase in angular resolution – resulting in the phenomenon of super resolution – may cause light field displays to evolve into super light field displays. At the time of writing this paper, however, no matter how advanced a single projection-based light field display system is, the human eye always focuses on the plane of the screen. This attribute is evidently desirable for the future light field displays as it makes visualization feel more realistic or at least more spatially present in general.

In a light field display with a 70 cm screen height viewed from a 2 m distance, and assuming a 5 mm pupil diameter, an angular resolution of at least 0.14 degrees is necessary to achieve a super resolution. Generally, if two distinct rays approach the eye from a given point of the screen, then both of these rays will enter the pupil, and the eye may therefore focus on different depth levels of the content. This definition of super resolution is also known as ‘high-density directional display technique’ in the work of Takaki [31].

As for the spatial resolution, there is no specific way of calculating or estimating how great it should be. The general rule here is that light field visualization should not suffer clearly perceptible degradations. It can be assumed that a minor level of blur due to an insufficient display and/or content spatial resolution may be tolerated and thus will not affect the perception of super resolution. Again, if the angular resolution satisfies the previously described optical conditions, then whether super resolution will be achieved will depend on the spatial resolution. It is important to note that an excessively high angular resolution cannot compensate for an insufficient spatial resolution, and vice versa.

A practical application where super resolution may significantly benefit the user experience will now be addressed. The work of Cserkaszky et al. [32] introduced a novel light field telepresence system. The greatest contribution of such application of the light field technology is towards the ‘sense of presence.’ If the human eye can focus on different depth levels of the communication partner via super resolution, then this can boost the sense of presence as the scenario becomes more natural and lifelike.

Although a telepresence system may indeed benefit from super resolution, it needs to be noted that such application by definition does not have a visual depth where super resolution can truly shine. A better example could be an automotive HUD, which practically necessitates a greater level of depth. If a spatial navigation application where the visualization is basically a combination of real-life visuals and projected components is considered, then super resolution may blend with visualization seamlessly, or at least less artificially. The importance of

super resolution in this use case scenario is also reinforced by the safety concern of having a driver focus separately on real-life depth levels and on a fixed-focal-distance visualization.

Basically any use case of light field visualization may be enhanced via super resolution, where depth values play a significant role in the overall user experience, and the relevant portion of the visualized content is thus sufficiently far from the plane of the screen. This can apply to industrial, medical, and entertainment purposes alike.

4.2. HDR

The technical term ‘high dynamic range (HDR)’ has two widely spread interpretations. First, it may refer to HDR-color imaging. In this sense, as opposed to the commonly used 8-bit or even 5-bit per-channel coding for low dynamic range (LDR) imaging, an HDR image can currently be coded using 10, 12, or 16 bits per channel. Different image formats (e.g. DDS or EXR) allow an image to be encoded using float-precision values: 16 or 32 bits per channel. The latter is used mostly for image processing and professional image editing applications, but rarely by regular end user programs.

Regarding light field, the implementation of HDR-color imaging seems to be completely dependent on the configuration of the display system at hand. For example, the widely used configuration of multi-view displays, based on the ultra-res LCD screen with a microlens array on top, does not seem to have any additional issue with adapting to HDR-color imaging, as opposed to its 2D counterpart.

The term HDR may also refer to HDR-luminance imaging. In this context, it is usually assumed that LDR images can utilize only the $[0,1]$ range for luminance while HDR images may have potentially unlimited storage ($[0,+\infty]$ range). Even for the case of 2D visualization, there are several active research topics on HDR-luminance imaging. Conditionally, they can be subdivided into two categories. The first category is the capturing of an HDR content with LDR cameras, and the second category is the visualization of HDR contents on LDR devices. The research in the latter category is mainly focused on how to make a conversion from the $[0,+\infty]$ range to the $[0,1]$ range in a way that would be plausible for the human visual system (HVS). This conversion operation is commonly known as tone mapping.

In a recent study, Eilertsen et al. [33] summarized the most prominent modern approaches for tone-mapping 2D video sequences, which are also applicable for still image processing. As the 3D display technologies are currently being actively developed, there is no similar state-of-the-art dissemination of knowledge for tone mapping

on light field displays. To the best of the authors’ knowledge, the only currently available papers on related topics are about tone mapping for VR [34], panoramic images [35], stereo images [36], or multi-view displays [37].

For the future research on tone mapping for 3D displays, three main directions can be cited. The first one is mimicking the existing 2D methods. For example, it seems straightforward to take Reinhard’s approach [38] of global tone mapping and apply it for a 3D display. The aforementioned approach requires global luminance estimation, which can be separately found per viewing position. For multi-view displays, this problem seems trivial; for real light field displays, such as the projection-based HoloVizio-like systems, Doronin et al. [39] may be referred to. Second, the ground truth tone-mapped 2D images for the series of observer positions can be defined, and then efforts can be made to approximate them by altering the 3D image in a display-specific format. Such approach will likely involve the constitution and solution of an optimization problem, which will depend both on the nature of the ground truth and on a particular display parameterization. Third, volumetric tone adaptation is possible. In this approach, for each particular point in a physical 3D space, a tone adaptation could be made for its local 3D neighborhood. This approach seems valid for volumetric displays and for Lambertian scenes, for which it can be assumed that any point in space emits light in all directions equally. For different types of light field displays and for non-Lambertian scenes, instead of the 3D neighborhood, the 5D neighborhood (space position and ray direction) of each point in space needs to be considered, which can be both ambiguous and computationally expensive.

4.3. High frame rate

High frame rate (HFR) visualization is a common label for any display technology above 60 Hz. In the case of the conventional 2D displays, the commercial HFR screens are typically 144–240 Hz, mostly for gaming purposes. Such displays can reach 400–600 Hz, but nearly 1000 Hz is also possible. The commercial projectors for stereoscopic 3D visualization support 240 Hz, which means that they provide 120 Hz per eye.

HFR visualization was not a research topic in the light field area at the time of writing this paper; in fact, to the best of the authors’ knowledge, there have been no published research results on the HFR light field so far. If the three future features discussed in this section are considered, it can be stated that while the other two have similar levels of potential contributions on visualization quality, the HFR light field has a lower scientific priority in comparison. This is due to the limitations in the use

case scenarios where HFR systems can truly benefit the users. Furthermore, the aforementioned bottleneck issue will still apply, reducing the achieved frame rate of visualization so that it will match the output of the slowest GPU.

Probably the most notable contribution of HFR light field systems is that in the case of hybrid visualization, where elements of the real world are combined with light field visuals; the smaller the perceived difference is, the better. The previously mentioned example of automotive HUD applies here as well. The sense of presence can also profit from such feature, making telepresence application more natural in appearance. Any utilization of the HFR light field with a critical user reaction time may be supported by this quality indicator, but it does not provide a universal benefit to visualization, as the other two do.

5. Conclusion

In this paper, the key performance indicators (KPIs) of light field visualization are reviewed and analyzed. It is highlighted throughout the paper that the excellent visual quality of this technology demands compliance with the requirements of the investigated attributes of both the system and the content. Also discussed are the ongoing research efforts, whose results will prove to be a great added value to the visualization quality and are expected to enhance the user experience. In time, the results of such research efforts will be integrated into the KPIs of light field visualization and will become fundamental properties of this technology.

Note

1. International Committee for Display Metrology (ICDM) and the Society for Information Display (SID): Information Display Measurements Standard (IDMS) v1.03.

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