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On the use-case-specific quality degradations of light field visualization

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ABSTRACT

Through the immense scientific efforts of the past two decades, light field visualization is now emerging in the industry, and commercial, everyday use cases are also expected to benefit from this glasses-free true 3D technology in the near future. While the technology itself may enable a natural 3D experience, there are, in fact, certain situations where visualization quality is not optimal. This can be due to the attributes of light field capture, transmission, compression, and numerous other factors that may degrade the perceived quality. However, the impact of such degraded quality fundamentally depends on the actual use case at hand. For example, while a specific amount of generic blur or disruption in the smoothness of the continuous horizontal and/or vertical parallax may cause minor inconveniences in a given use case, it may result in significant errors and substantial issues in another. In this paper, we analyze the use-case-specific quality degradations of light field visualization. Each and every key performance indicator of light field visualization quality is addressed, and their effects are separately studied in the context of each use case. Display and content parameters, such as angular resolution, are examined on the level of individual and combined thresholds. The investigated use cases cover industrial, medical, commercial, educational, cultural and communicational scenarios. Therefore, both active and passive utilizations are considered, and a special emphasis on task performance is included in this paper.

Keywords: Light field, key performance indicator, parallax effect, perceived quality, task performance

1. INTRODUCTION

Light field displays offer glasses-free 3D visualization. While this generic statement can serve as a more-than-adequate opening sentence for numerous scientific publications, one must not forget that this is, in fact, one of the greatest strengths of light field visualization in general; no cumbersome glasses or other viewing equipment is necessary to fully enjoy the 3D visual experience. Yet on its own, this attribute is far from being sufficient to satisfy the viewers, not to mention that specific professional environments have significantly stricter requirements towards visualization quality. Therefore, light field displays and their visualized contents must comply with quality requirements that are appropriate for their use cases. Still, in certain situations – many of which are rather common – light field visualization may suffer different types of quality degradation.

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Similarly to conventional 2D visualization, several technical phenomena can degrade the quality of the content. As a matter of fact, the origin of most visual impairments is rather analogous to the case of 2D imaging, as they usually come from issues related to content capture, transmission and compression. However, these are extended by matters of 3D visualization, like unsuitable, simply inapt synchronization during a multi-camera capture.

Regardless of the origin of the degradation, the reduced visual quality may affect not only the general viewing experience, but in case of professional contexts, the related task performance as well. Visual impairments apply to the key performance indicators (KPIs) of the technology, and through the degraded KPIs, visualization quality is negatively influenced. Light field KPIs include spatial, angular and overall resolution, depth budget, field of view (FOV), brightness and contrast. It is important to highlight that most KPIs are applicable to both the display system and the visualized content.

In this paper, we present our analysis of light field visualization quality degradation. Visual impairments are approached from the angle of KPIs, and their effects are separately addressed in the contexts of industrial, medical, commercial, educational, cultural and communicational use cases. Our work particularly focuses on task performance and usability, and emphasize the severity of each degradation type within the investigated scenarios. Within the scope of this publication, the analysis is applied to projection-based light field visualization.

The remainder of the paper is structured as follows: Section 2 briefly reviews the scientific contributions related to light field visualization quality. The use-case-dependent analysis of the degradation types is introduced in Section 3, separately for KPIs. Section 4 provides additional points of discussion on the addressed topics. The paper is concluded in Section 5.

2. RELATED WORK

Our earlier works on the quality of light field visualization address spatial resolution,[1] angular resolution[2] and FOV,[3] and also review the relevant KPIs.[4] While such characteristics of content and display are directly studied – e.g., by the research efforts of Kovacs *et al.*[5,6] – yet the majority of the scientific literature on light field visualization approaches the topic of quality degradation via compression. Kovacs *et al.*[7] investigated H.264/MVC, Adhikarla *et al.*,[8] Ahar *et al.*,[9] Bakir *et al.*,[10] Paudyal *et al.*,[11] Perra *et al.*,[12] Recio *et al.*,[13] Shi *et al.*[14] and Tian *et al.*[15] involved H.265/HEVC. The utilization of JPEG and JPEG 2000 is also frequent in the literature, like in the work of Shan *et al.*[16] and in several of the previously listed scientific publications using HEVC. Further degradations include Gaussian noise (also quite common, e.g., Adhikarla *et al.*[8]), VP9 coding (e.g., Viola *et al.*[17]), WAC coding (e.g., Ahar *et al.*[9]), VVC coding (e.g., Bakir *et al.*[10]), LFTC coding (e.g., Palma *et al.*[18]), encryption (Wen *et al.*[19]), watermarking (e.g., Paudyal *et al.*[20]), light field reconstruction (e.g., Kara *et al.*[21]) and view interpolation (e.g., Cserkaszky *et al.*[22]).

3. VISUAL QUALITY DEGRADATION ANALYSIS

In this section, visual impairments are addressed through KPI degradation, and their effects on the investigated use cases are detailed separately for each KPI. Combined effects – such as interdependencies – and further types of visual impairments are analyzed at the end of the section.

3.1 Overview of the investigated use cases

The use cases were selected based on their relevance to the potential utilization of light field technology. As light field displays are already emerging in certain areas (e.g., industrial use cases) and other areas receive particular attention (e.g., medical use cases), our choice of use case inclusion was supported by the state-of-the-art scientific works and the state of the market at the time of this paper.

3.1.1 Industrial use cases

Industrial use cases encompass everything related to industrial activities; every scenario in which light field visualization may benefit the stakeholders. This includes prototype visualization, resource exploration, traffic control and many more. The observers are typically professionals of their respective fields and the visualized content may affect decision-making processes. Furthermore, certain use cases may involve highly safety-critical procedures, and thus, visual quality is of the essence.

3.1.2 Medical use cases

Medical use cases are generally the most quality-sensitive scenarios of our analysis, as visual degradation may lead to diagnostic inaccuracy, potentially resulting in instances of false positive and false negative. One particularly relevant segment of the medical field is radiology, especially due to the synergies of light field scene reconstruction and medical image reconstruction.[23] The observers are highly trained medical experts, in possession of the know-how where to look in a given medical image when evaluating the obtained data. 3D visualization is already present in healthcare, and the emergence of light field technology may enhance the related processes.

3.1.3 Commercial use cases

Commercial use cases include a wide variety of utilization purposes. One rather illustrative use case is digital signage, which has been around for so many decades now, but its natural 3D variations may introduce new levels of immersion and visual attraction. The observers are mostly walking pedestrians and individuals traveling in vehicles. Therefore, observers are most likely to effortlessly view the visualized commercial content from a continuous variety of viewing angles. There are many other commercial use cases as well, some of which may depend a lot on high-quality visualization.

3.1.4 Educational use cases

Educational use cases cover both general education and specialized training. The latter may include medical training and engineering courses, both of which may pose strict requirements towards quality. The observers are generally students of different levels of education, but specialized training may also apply to transportation professionals (e.g., land vehicle driving simulation), military personnel (e.g., aircraft piloting simulation) and many more.

3.1.5 Cultural use cases

The most common form of cultural use cases is cultural heritage exhibition. The observers can be of any age and background, and the contents are typically viewed by many observers simultaneously. Possibly the greatest relevance of cultural use cases in the context of light field imaging is that it is a rather popular practice that novel visualization technologies are used to make cultural heritage more attractive, immersive and engaging.

3.1.6 Communicational use cases

The most apparent form of communicational use cases for light field visualization is light field telepresence. It aims to provide a sense of presence by representing the communicating parties in natural 3D. Similarly to cultural use cases, any individual may be an observer, a user of telepresence systems. From all the use cases addressed in this paper, this is the only one which commonly relies on the transmission of light field data, which may introduce issues regarding visualization quality. Finally, it should be highlighted that the content in such a context is rarely static, which can be combined with the fact that content dynamics may mask the different types of quality degradation – distortions in static contents are significantly easier to detect and they have a greater impact on the perceived quality of light field visualization.

3.2 Spatial resolution

3.2.1 Introduction to the KPI

The spatial resolution of light field displays and contents can be imagined as the conventional 2D-equivalent resolution. In fact, light field displays are capable of visualizing 2D contents; in such case, the same view may be observed from any given position within the FOV. Let us assume that we have a series of 2D images that are created via a virtual camera; the camera faces a virtual scene while moving along either a line or an arc, and captures the scene at uniform intervals. Let us also assume that the process of capture (i.e., rendering) is defined with parameters that are suitable for a given light field display. If we provide this set of images and the parameters of capture to the converter of this specific display, then we obtain a light field that can be properly visualized on the display. In this case, the spatial resolution of the content is practically the 2D resolution of the rendered images. Regarding the display, the corresponding value is determined by the optical engines.

3.2.2 Degradation description

Now that we know how to imagine spatial resolution, let us discuss how its insufficiently low values may affect perceived quality in general. If we have a 2D computer monitor, lowering the resolution of a fullscreen application (e.g., a video game) results in fewer but larger pixels (i.e., blockiness). While this may serve as a good starting point to understand low spatial resolution in the context of light field visualization, there are certain attributes that must be highlighted. First and foremost, the pixel grid of a 2D computer monitor is completely uniform, and this typically does not apply to light field displays due to the irregular light ray propagation. Secondly, the perceived "shapes and sizes" of such pixels fundamentally depend on the viewing angle of the observer. Finally, content conversion commonly interpolates the source 2D images to match the properties of the projector array. Therefore, the resulting degradation is blur instead of blockiness.

3.2.3 General effects on perceived quality

A limited extent of blur is not necessarily harmful to light field visualization quality. In fact, even greater extents may be tolerated in case of rendered, artificial contents,[1] as the additional blur may be perceived as a form of antialiasing. However, blur may be particularly disadvantageous for specific quality-sensitive use cases.

3.2.4 Industrial use cases

Blur is tolerable in industrial contexts if and only if the visualized content does not contain small, highly-detailed components – or it does, but they are not crucial to the whole – and the sharpness of the surface textures and the fine details of the 3D structure of the shown entity do not play a major role in the related actions (e.g., decision-making processes). Such can be the presentation of the design of a new building to board members, investors or a committee. While high spatial resolution could actually benefit this use case – particularly when investors are involved – still, a reasonable extent of blur does not have an effect on the core function of visualization, which is to present the overall design and to show the building as a proportionate whole in 3D. However, blur is not tolerable in case of most industrial prototype reviews, as such contents tend to contain small but important components, and textures and structures the sharp visualization of which is vital to the use case.

3.2.5 Medical use cases

Medical visualization is highly sensitive to most types of degradation. The indicators of the majority of serious illnesses are often relatively small – particularly in early stages of the disease, during which treatment is more likely to succeed. Along every single aspect, the detection of such small indicators is more critical than the proper perception of small components in industrial use cases. Therefore, the blur caused by insufficient spatial resolution is not tolerable at all for medical cases.

3.2.6 Commercial use cases

Unlike the previous two use case categories, a high portion of commercial contexts tolerate blur rather well. Let us take digital signage as an example. The primary purpose in many cases is to deliver information, accompanied by impressive visuals. As long as the information can be effectively delivered (i.e., visualization is sharp enough for texts to be readable), the "impressiveness" of the graphics can tolerate blur (of course, depending on the actual content), since it relies more on the angular component of visualization. Generally speaking, the commercial use cases of light field technology aim to grab the attention of individuals through the 3D nature of the content and focus less on its sharpness.

3.2.7 Educational use cases

As the forms of education may vary a lot, their associated requirements towards spatial resolution may vary a lot as well. For example, presenting different flora and fauna to high school students may tolerate blur to some extent, but showing mechanical components to students of a technical university may hinder the purpose of education. Not to mention that the context of medical education is approximately as sensitive as medical use cases themselves.

3.2.8 Cultural use cases

The 3D exhibition of cultural heritage is rather tolerant towards blur. While the representation of paintings – the typical 2D scenario – may be horribly degraded by blur, presenting a sculpture or a less-detailed artifact via light field visualization may be done in a considerably lower spatial resolution – especially compared to the previous use cases. Even if certain items were originally created with fine details through excellent craftsmanship, these details are often chewed away by the iron teeth of time. Naturally, if such details are actually preserved, or if they are recreated through archaeological modelling, then having a high spatial resolution is indeed relevant.

3.2.9 Communicational use cases

The highest extents of blur are tolerated by the communicational use cases of light field technology. This might sound like a strong statement – perhaps too confident and strong. Still, let us state from all the investigated use cases, these ones rely probably the least on spatial resolution. First of all, the sense of presence fundamentally originates from the 3D nature of visualization and life-like proportions (e.g., in case of a human-sized light field telepresence system[24]). Moreover, blur usually does not affect the function of communication, only its perceived quality. In contrast, several previously mentioned use cases may be severely affected by blur on the level of function. Additionally, the minuscule details of the human body and face do not really benefit the sense of presence and user experience in general.

3.3 Angular resolution

3.3.1 Introduction to the KPI

Let us assume we have a light field display that supports horizontal parallax. This means that if we, as observers, move from the left to the right or vice versa, then what we see as visualized content will change, just as in real life. Additionally, parts of the content closer to us change faster than parts further away. This phenomenon is known as the parallax effect, the perceived smoothness of which is defined by angular resolution. Formally, the angular resolution of a light field display is the minimal angle of change that rays can reproduce with respect to a single point on the screen;[25] the smallest angle between two neighboring independent light beams emitted from a screen point. Regarding the angular resolution of the visualized content, if we continue the demonstrative example of the previous subsection, then while spatial resolution is the 2D resolution of the rendered images, angular resolution is the number of rendered images compared to the FOV. For example, if we render 90 source views for a 45-degree FOV, then the angular resolution is 2 views per degree. It means that we have a source view for every 0.5 degrees of the FOV. At the time of this paper, both in industry and academia, the common practice is to say that the angular resolution in this case is 0.5 degrees.

3.3.2 Degradation description

Saying that angular resolution defines the perceived smoothness of the parallax effect is slightly abstract, so let us elaborate this statement. According to the previously stated formal definition, the higher (i.e., numerically lower in its degree format) the angular resolution of a display and its visualized content is, the smaller angular change is required to perceive a different angle of the content. In a normal (i.e., functionally acceptable) case, the extent of this angular change is so small that the display can address the two eyes of the observer with two distinct light rays – hence, 3D vision.[26] If this is not the case, then 3D vision may be compromised.[27] Furthermore, low angular resolution means that the adjacent source views interfere with each other (i.e., crosstalk effect) and the lower the angular resolution is, the more likely it is to perceive sudden jumps between discrete views. In this case, the parallax effect is still in place as the perceived change rate of objects in a visualized scene depend on the distance relative to the observer, but the transition is no longer smooth.

3.3.3 General effects on perceived quality

Issues related to insufficient angular resolution tend to severely penalize visual quality. As indicated by the scientific literature, in general, observers are more perceptually sensitive to low angular resolution than to low spatial resolution. Visual impairments particularly apply to contents that "come out of the screen" more; as angular resolution is the best in the plane of the screen, contents with greater depths values are more susceptible to the visual degradation caused by low angular resolution.

3.3.4 Industrial use cases

Similarly to what was stated earlier in the analysis on low spatial resolution, visually demonstrating relatively simple structures and objects may endure insufficient angular resolution. If the crosstalk effect does not significantly impact the general perception of the visualized scene, the disturbances related to the smoothness of the parallax effect may be tolerated. Indeed, in most of the industrial use cases, the transition between the points of observation (i.e., where the observer spends a longer time in one place to view the content) is typically not as important as the perceived quality itself. However, the perceived quality of light field visualization may suffer notable issues if the content is more complex or has greater depth values. For example, in case of a prototype review, smaller components further from the plane of the screen may become unrecognizable.

3.3.5 Medical use cases

The aforementioned statement regarding the small components of a prototype apply to the small indicators of medical visualization as well. In fact, the crosstalk effect may completely mask these health abnormalities, leading to a false negative. At the same time, crosstalk may also result in false positive, should the adjacent views overlap in such a semi-transparent manner that the shade of the part of the medical content appears to be darker relative to its surroundings.

3.3.6 Commercial use cases

While commercial use cases may also suffer the visual impairments caused by low angular resolution, they tend to be more resilient, especially when observers are moving and the visualized content is not the sole element of focus (or only for a brief time period). This description matches digital signage very well, and therefore, such displays of commercial contents may tolerate crosstalk more. As the viewing angle of an observer typically changes continuously – and sometimes rapidly – this may compensate the degraded smoothness of the parallax effect. Furthermore, because of the basic properties of the use case, the content itself does not need to have greater depth values; in fact, it can be relatively flat.

3.3.7 Educational use cases

All forms of education may be easily affected by low angular resolution, but its effect may be the most significant on specialized training. If the specific context of light field visualization in education has the flexibility for suboptimal content representation (e.g., such as poor-quality photo copies or bad sound quality during a listening exercise), then certain extents of crosstalk may be tolerated. In these scenarios, the educational message may still get through, maintaining the function of the use case. For example, imagine a scenario where the students are introduced to the proportion differences between animals. Although the animals are visually degraded through low angular quality, they are still recognizable and the size differences are apparent. The considerations for specialized training are analogous to those of industrial and medical use cases.

3.3.8 Cultural use cases

On the one hand, the exhibition of cultural heritage is commonly a highly mobile scenario, and thus, movement may compensate issues related to the 3D perception of the content. On the other hand, such content is often notable in dimensions, hence, low angular resolution penalizes visualization quality at greater depth values. All influencing factors considered, cultural use cases are moderately resistant against the effect of crosstalk, highly depending on the structural components and the dimensions of the visualized content.

3.3.9 Communicational use cases

Compared to spatial resolution, insufficient angular resolution may affect the perceived quality of communicational use cases more. As stated earlier, the sense of presence is influenced more by angular quality. Still, the overall impact on such use cases may not be as severe as in case of the previously detailed scenarios. One notable factor is that the human face (which is the de facto focus of visual communication) has well-defined, rather limited depth ranges. Because of this, considerations related to greater depth values do not penalize the visual quality of communicational use cases.

3.4 Depth budget

3.4.1 Introduction to the KPI

The depth budget of a light field display determines how much the visualized content may diverge from the plane of the screen. The measure of this extent is perpendicular to the screen, and it is usually symmetrical in the two directions. The one coming towards the observer is the positive depth budget, the opposite direction is called the negative depth budget.

3.4.2 Degradation description

The smaller the depth budget is, the smaller the maximum possible content divergence from the plane of the screen is, and therefore, it is more difficult to differentiate depth levels. This evidently affects how the parallax effect is perceived. In order to demonstrate its influence on the perceived parallax, let us imagine two similar (or even identical) static objects in a scene. If one of them is notably further away from the observer than the other, then even a slight observer movement may indicate that while the closer one already changes its relative perceptual position to a given extent, the other is less affected or perceptually unvarying.

3.4.3 General effects on perceived quality

The most significant issue with constraining a light field scene to a small depth interval is it may degrade the overall 3D visual experience. The relative perceptual depth distances are limited, and it may even affect entities that are larger in size along the axis.

3.4.4 Industrial use cases

In the industry, limitations regarding depth are often less penalizing than insufficient spatial or angular resolution. Yet this fundamentally depends on the spatial structure of the visualized content. As many industrial use cases are not that time-critical (e.g., well-thought-through decision-making processes), careful perceptual examination of the content may compensate most issues related to limited depth.

3.4.5 Medical use cases

In use cases of medical visualization where relative sizes and distances are vital to diagnosis, limited depth may lower assessment accuracy, and generally, it may make the affected use cases more exhaustive for medical experts, as more time and effort is required to reach a certain level of professional confidence regarding the diagnosis. However, medical contents that comfortably fit into the depth range of visualization are less affected or completely unaffected.

3.4.6 Commercial use cases

Commercial use cases that commonly involve high levels of user mobility do not suffer the limitations of depth much. For example, in case of digital signage in public spaces, visualization may easily serve its core purpose (i.e., showing the content in natural 3D) without greater extents of depth. However, it needs to be noted that the efficiency of the use case may be severely impacted, as the lack of depth may result in less attention, since the 3D nature of the visualized content is essentially demonstrated via depth.

3.4.7 Educational use cases

Limitations regarding depth in the context of general education may not influence usability as significantly as for specialized training; considerations are primarily analogous of those of industrial and medical use cases. Demonstrative education activities may endure these limitations, but it is important to point out that reduced extents of depth may make such activities less engaging, less attractive.

3.4.8 Cultural use cases

Since use cases of cultural heritage and culture in general often involve user movements, similarly to digital signage, limited depth is not considered to be that much of an issue, in comparison to other forms of degradation. However, the considerations of commercial and educational use cases apply here as well, since less attention is indeed harmful to such purposes.

3.4.9 Communicational use cases

Since communicational use cases are usually comparably more static with regards to observer movement, the aforementioned compensation of limited depth does not necessarily apply. This means that the visualized communicational partner(s) may appear less 3D, more flat 2D. While this does not notably affect the basic function of telepresence (i.e., visualization is still clear, without any major visual artefact), it may still negatively impact user experience at the end of the day. However, keep in mind that the human face is rather limited in depth, and therefore, this form of degradation in the context of communicational use cases may go more-or-less unnoticed, in comparison to the others.

3.5 Field of view

3.5.1 Introduction to the KPI

The FOV of light field visualization is not to be confused with the FOV of other technologies. It is not measured from the perspective of the viewer; instead, it is measured from the display. The FOV is basically an angle that sets the boundaries of the area in which the visualized content is visible. To be more precise, certain portions of the content are visible from outside the FOV as well, but the proper perception of light field visualization is limited to the FOV. As an example, if a light field display has an FOV of nearly 180 degrees, then visualization may be properly perceived from any angle in front of the display, without experiencing missing content portions.

3.5.2 Degradation description

Depending on the actual implementation of the light field displays, the content starts to fade out as the observer leaves the FOV; the greater the distance from the edge of the FOV, the higher percentage of the content is perceptually absent. Therefore, observers should remain inside the FOV during the usage of light field systems – or rather, use-case-oriented light field displays should be designed with an FOV that accommodates typical observer behavior.

3.5.3 General effects on perceived quality

As said, the FOV determines the angle of the valid area of observation, with respect to the screen. The smaller the FOV is, the more constrained this area is. It implies restrictions towards the number of simultaneous viewers and the movement of the viewers.

3.5.4 Industrial use cases

For most industrial use cases, if the utilization of light field visualization is either limited in terms of observer mobility – and it is functionally adequate to view the content from a limited angle – or the associated tasks are not time-critical, then a small yet sufficient FOV shall not pose an issue. As a counter-example, in case of a prototype review, a small FOV does limit the number of simultaneous viewers, but since such procedures are usually not time-critical, on its own, this is not a major disadvantage. However, a prototype review commonly mandates that the visualized entity is observable from a large variety of angles. This can, of course, be easily compensated by content rotation. In the contexts of all the use cases, "small yet sufficient FOV" means that a single individual may view the content from a specific position without being located outside the FOV during natural head and body movement (i.e., idle sideways sway). The appropriate FOV for this depends on the viewing distance – the closer the observer is, the larger FOV is required.

3.5.5 Medical use cases

Medical evaluation is analogous in many ways to industrial use cases when addressing the issue of a small FOV. The content typically needs to be observed from a wide variety of views, but content rotation may solve that. Also, the diagnosis is often provided by a single medical expert. Therefore, a small yet sufficient FOV may be adequate. However, since such procedures may be time-critical, content rotation is necessarily a valid option. Furthermore, certain medical use cases may require more simultaneous viewers, such as medical consulting scenarios.

3.5.6 Commercial use cases

While many industrial and medical use cases may tolerate a small FOV under the right circumstances – especially if content rotation is an option – certain commercial use cases fundamentally rely on a wide FOV. For example, in case of digital signage, the FOV needs to be as big as possible. Even if we consider units of digital signage on the sidewalk that are particularly directed towards pedestrians, a relatively wide FOV is necessary to properly cover this restricted use case.

3.5.7 Educational use cases

The different usage contexts of education commonly enable content rotation, and thus, a small FOV may not have such an impact. Moreover, many instances of education do not involve observer movement. The only main consideration here is whether the educational light field visualization is for a single individual or a group. In case of the latter, either a wider FOV is required to accommodate the simultaneous viewers or the viewing must be organized in a turn-based fashion.

3.5.8 Cultural use cases

Due to the typically high numbers of simultaneous viewers, a wide FOV tends to be necessary for cultural use cases. It is important to add here that content rotation may very well be an option, especially since digital user interaction is a common method to increase the level of engagement at exhibitions of cultural heritage.

3.5.9 Communicational use cases

The FOV requirement of communicational use cases of light field visualization depends on the actual system implementation. In case of static, either TV-like or mirror-like representations – such as the telepresence system of Holografika[24] – smaller FOV values may be acceptable. However, mobile systems – such as the LightBee of Zhang *et al.*[28] – naturally require wider FOV.

3.6 Brightness

3.6.1 Introduction to the KPI

Brightness in the context of light field displays is the photometric measure of luminous intensity per unit area – hence the unit cd/m^2 – measured at the screen. During measurement, a completely white image is visualized, since that produces the highest possible level of brightness.

3.6.2 Degradation description

The sufficiency of brightness depends on the environment of the investigated use case (i.e., lighting conditions) and its purpose-oriented requirements. Basically, some use cases may be exposed to high level of environmental illumination (e.g., particularly bright sunlight), while some others may necessitate flawless visibility – the combination of the two is not common, but exists. In case of insufficient brightness, the content is less visible, which may significantly impact the use case.

3.6.3 General effects on perceived quality

The most important effect of insufficient brightness on perceived quality is that the visual information may not be delivered with the required confidence. This, on its own, may completely hinder certain use cases. Generally speaking, beyond usability, low brightness negatively influences the attractiveness of light field visualization as well.

3.6.4 Industrial use cases

Most industrial use cases are favorable in the sense that lighting conditions are typically adjustable, eliminating the issues of the utilization environment. In such usage context, it is an essential requirement that the lack of sufficient brightness does not affect perception. There are, of course, examples, in which suboptimal brightness is tolerable. For example, during the presentation of a less-complex design concept, low brightness may not have a notable impact, in contrast to prototype review, where it may result in the visibility issues of small yet significant components and structures.

3.6.5 Medical use cases

Having insufficient brightness during medical use cases may easily result in false negative diagnosis, particularly when it comes to the perception of small indicators. Fortunately, the environment of medical evaluation is usually more than adequate with regards to lighting conditions.

3.6.6 Commercial use cases

Commercial use cases may be severely affected by insufficient brightness, depending on location. For example, the vast majority of digital signage is located outside, where lighting conditions are (nearly) impossible to control. Practically, brightness in such context should be chosen so that visualization is perceptually acceptable and attractive in the sunniest, brightest weather.

3.6.7 Educational use cases

Many forms of educational use cases may be affected by insufficient brightness, yet the most relevant – and most susceptible – use case is specialized training via light field HUDs. Such HUD can be the windshield of a vehicle, regardless whether it is a land, sea or air vehicle. Without sufficient brightness, the windshield might be unable to convey the visualized information with the necessary level of reliability, hindering the purpose of training.

3.6.8 Cultural use cases

The effect of insufficient brightness on cultural use cases fundamentally depends on the location, similarly to commercial use cases. If it is an indoor exhibition, brightness is typically not an issue – unless there are larger windows without curtains during a sunny day. Outdoor exhibitions are significantly more impacted, yet the occurrence of such is rather unlikely, as it would expose the expensive light field system to potential environmental damage.

3.6.9 Communicational use cases

The communicational use cases of light field visualization are typically indoor scenarios with adjustable lighting conditions. While insufficient brightness may affect the perceived quality, certain extents of such degradation may be tolerated. In any case, altering the brightness of the use case environment may easily compensate the relevant visual issues.

3.7 Contrast

3.7.1 Introduction to the KPI

The contrast of light field displays may be measured in different ways. The most common practice in the field is the on / off contrast, also known as the full on / full off (usually abbreviated as FOFO) contrast, which is the ratio of full white and full black brightness. However, light field display manufacturers tend to consider the ANSI (American National Standards Institute) contrast as well, which relies on the visualization of patterns (i.e., checkerboard), using only fully black and white colors. It is the ratio of white average brightness of black average brightness. Its relevance is further detailed in the discussion.

3.7.2 Degradation description

Insufficient contrast is similar to insufficient brightness in the sense that they both lead to the loss of visual information. While low brightness generally degrades the entire visualized content, low contrast primarily penalizes portions of the content where the differences in brightness are less significant. In other words, it makes such parts of the content perceptually impossible to distinguish.

3.7.3 General effects on perceived quality

Poor contrast properties can severely degrade the perceived quality of light field visualization. The missing visual information may affect the perception of structure, surface texture and practically any component of the content which is the result of subtle changes in light intensity. From the perspective of technology utilization, it might be worse than insufficient brightness. If brightness is low, then it is usually apparent to the viewer. However, if a content has multiple adjacent areas with great differences in light intensities, then the degradation of other parts with subtle differences may go unnoticed. Unnoticeable objective visual degradation may actually be beneficial in certain contexts (e.g., perceptual coding); however, its effect on certain use cases may be particularly harmful and it may hinder the associated purpose(s).

3.7.4 Industrial use cases

In case of many previously detailed forms of degradation, smaller parts of contents are particularly vulnerable to visual impairments. In case of insufficient contrast, even larger components may be just as affected, due to the aforementioned smaller discrepancies in light ray intensities. During prototype review, 3D rendering techniques often do not enhance the content contrast, in order to produce consistently realistic visuals. Even if the contrast is globally enhanced, it does not serve as a universal form of compensation for this degradation.

3.7.5 Medical use cases

Insufficient contrast is probably the worst type of degradation that can happen to medical use cases. Technically, it can make indicators of different sizes completely invisible, resulting in false negative evaluation outcomes. The purpose of such assessments is to detect diseases in early phases; the earlier, the better, as treatment has a higher chance of success. Yet such earlier phases have indicators that differ less from their environments, making low visualization contrast a major threat.

3.7.6 Commercial use cases

While insufficient contrast may negatively impact commercial use cases as well, it needs to be noted that such content is usually created with high contrast. After all, the primary purpose of numerous commercial use cases is to grab the attention of individuals, and high contrast achieves that very well. Therefore, in many cases, low contrast may actually be less harmful to commercial usage than low brightness.

3.7.7 Educational use cases

Let us take the example of specialized training via light field HUD, introduced in the subsection of insufficient brightness. Issues related to contrast may make information retrieval challenging, confusing, and beyond a certain level of degradation, the entire light field visualization just becomes a distraction. Even though the visualized content is typically designed with the highest possible contrast, the user must be able to confidently differentiate the content from the natural view. There are, of course, forms of general education which are significantly less susceptible to low contrast.

3.7.8 Cultural use cases

One particular issue of cultural use cases is that the exhibited content is not necessarily compatible with contrast enhancement. Furthermore, physical artifacts of human culture are often unvarying in terms of contrast – or at least they do not have much variation. For example, many preserved ancient artifacts have the same color and texture across the surface of the entire entity.

3.7.9 Communicational use cases

Due to the redundancy of the human face – particularly the skin – communicational use cases are more resilient to low contrast. The key elements of the human face during a conversation are the eyes and the mouth, as their momentary shape and behavior conveys the most non-verbal information. Of course, details, such as the wrinkles of the forehead, may disappear, yet the eyes and the mouth have a contrast to remain sufficiently visible.

3.8 Further impairments and considerations

3.8.1 Interdependencies between spatial and angular resolution

As a quick recap, low spatial resolution means blur, and low angular resolution disturbs the smoothness of the continuous parallax. What happens when both apply to the visualized content? Frankly, the perceived quality is most likely to be poor. However, the blur induced by low spatial resolution may actually slightly compensate the parallax.[29] To be more precise, it does not factually improve the smoothness of the parallax effect, but on the level of human perception, the blur helps masking the severity of angular degradation.

3.8.2 Overall nominal resolution and optical efficiency

While spatial and angular resolution are individually important – particularly angular resolution – the overall nominal resolution plays a more vital role in the industry. It is crucial to point out that optical efficiency has an immense impact on the effective resolution of the visualization. It is the ratio of the overall resolution and the projected resolution. If the optical efficiency is 75%, then it means that a quarter of the projected resolution does not benefit the use case, as it does not get visualized. In practice, this value is commonly between 80% and 90%, and the best light field systems may reach optical efficiency around 95%.

3.8.3 Visualization sharpness inside and outside the plane of the screen

An inherent de facto issue of light field visualization is that the content is the sharpest inside the plane of the screen of the display. If we want depth – which is quite necessary for 3D visualization – then we need the content to leave this plane. However, outside the plane of the screen, the same level of sharpness is not an option; it cannot be achieved. Therefore, content should be aligned in a way that the most important parts and components are located inside the plane of the screen.

4. DISCUSSION

The first point of discussion is that light field visualization must comply with all the KPI requirements simultaneously, for both the display and the content. It is rather intriguing when a manufacturer declares that their novel display is capable of 300 megapixels, but the detailed KPI values are quite relevant as well, especially since one may not necessarily be able to compensate the other.

This brings us to our other point of discussion raised in this section, which is that light field KPIs are fundamentally intertwined; they affect each other a lot. Let us take for instance angular resolution and FOV, and think on the level of source views. If we have a total of 50 source views, then for example, this can be a system with a 100-degree FOV and a 2-degree angular resolution, a 50-degree FOV and a 1-degree angular resolution or a 25-degree FOV and a 0.5-degree angular resolution. The first option may be adequate for cultural heritage exhibition or digital signage, the second one may suit specialized training and telepresence, while the third one may benefit highly-focused industrial and medical use cases. As an additional example of KPIs affecting one another, let us now consider angular resolution and contrast. The contrast of light field displays is often tested by thin, alternating black and white stripes. However, if the angular resolution of the display is not high enough, then at a certain distance, the alternation of these stripes cannot be properly perceived.

5. CONCLUSION

In this paper, we reviewed the use-case-specific quality degradations of light field visualization. The analysis indicates that the magnitude of the effect of issues related to certain KPIs may vary significantly for different use cases. We conclude that while it is indeed important to be aware of the impact of individual KPIs, but their interrelations should be considered as well. Furthermore, we highlight that light field visualization should adhere to all the requirements simultaneously, which is far from being an easy and straightforward task.

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