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3D battlespace visualization and defense applications on commercial and use-case-dedicated light field displays

Peter A. Kara[a,b], Tibor Balogh[c], Mary Guindy[c,d], and Aniko Simon[e]

[a]Budapest University of Technology and Economics, Budapest, Hungary
[b]Kingston University, London, UK
[c]Holografika, Budapest, Hungary
[d]Pazmany Peter Catholic University, Budapest, Hungary
[e]Sigma Technology, Budapest, Hungary

ABSTRACT

Light field visualization technology has started emerging through commercially-available devices, and while its appearance on the consumer market is somewhat already on the horizon, the day light field displays integrate into our quotidian activities is still yet to come. However, just because light field displays are not part of our everyday lives yet, that does not mean that they do not already contribute to professional usage contexts. One such use case category is defense applications, where the daunting development and manufacturing expenses of these devices do not really intimidate the available budget. In fact, modern warfare is heavily investing into novel visualization technologies and cutting-edge innovations for both those who serve on the battlefield and those who devise strategic maneuvers and tactical decisions. The latter is essentially the process of making decisions based on a vast amount of data. The success of such process is fundamentally affected by the efficiency of the delivery of the available and the projected information. In this paper, we present our work on light field battlespace visualization and other relevant applications of light field for defense and warfare purposes. Beside conventional approaches, we propose multiple alternative solutions that best fit the investigated use cases. Our work prioritizes visualization quality and user interaction. Regarding system attributes, particular attention is paid to the field of view and the angular resolution of such devices. We separately address the utilization of commercial devices and the use-case-centric design of dedicated hardware.

Keywords: Light field visualization, 3D battlespace, field of view, angular resolution, user interaction, use-case-centric design

1. INTRODUCTION

One of the greatest milestones in the evolution of warfare-related tactical and strategic planning was the introduction of real-time communication. It significantly reduced the end-to-end delay between high-level decision makers and those who serve on the battlefield, thus increased responsiveness and situational adaptation. For numerous centuries, the state-of-the-art approach was that decision makers stood around a table, covered in large, unfolded maps and small, symbolic items, representing military resources. This changed during the second half of the 20th century, as the visualization of the battlespace started to become digital. Today, the continuous and rapid development of digital technology – particularly visualization technology – greatly benefits defense applications, providing their users more situational awareness than ever before. It can be stated that the past few decades were quite fruitful in this regard, since the emergence of 3D visualization technologies empowered military research, leading to the enhancement of existing use cases and the deployment of novel ones. With the available 3D visual data, decision makers may now absorb much more information, which ultimately assists the cognitive processes of tactical and strategic planning.

Further author information: (Send correspondence to Peter A. Kara)
Peter A. Kara: E-mail: kara@hit.bme.hu
Tibor Balogh: E-mail: t.balogh@holografika.com
Mary Guindy: E-mail: m.guindy@holografika.com
Aniko Simon: E-mail: aniko.simon@sigmatechnology.se

From all the available 3D visualization technologies, light field displays should definitely be highlighted, as they provide glasses-free 3D experience without the need of additional viewing devices. This simple fact comes with three major implications: (i) the usage of light field displays is not "cumbersome" (e.g., there is no need for a bulky headgear), (ii) they enable a more natural sensation, and (iii) they can be viewed by many individuals simultaneously. The combination of the first two implications means that individuals may use such displays for extended periods of time, which is essential to specific use cases of defense applications. The third implication is more relevant to the classic format of battlespace visualization, where decision makers stand around the representation of military activities. Additionally, the second implication enables inter-personal interactions between the viewers, which is absolutely essential if multiple individuals contribute to a specific tactical or strategic decision. Technically, the viewers may seamlessly change visual focus between the visualized battlespace and each other – no interaction related to viewing devices is necessary to switch between the two (e.g., no need for glasses to be taken off).

Of course, it should be noted that applications of augmented and extended reality have immense potential for battlespace visualization as well, and the authors do not claim that light field technology is clearly superior in every single aspect. However, the lack of the need for special glasses or contact lenses does make the 3D visual sensation more natural. Yet, the inclusion of personal viewing devices may in fact provide particular benefits, such as assess control. For example, only military personnel above a given level is granted access to view the battlespace, while in case of light field, anyone within the Field of View (FOV) and line-of-sight of the content may perceive it. It is not the purpose of this paper to compare light field systems and other solutions of 3D visualization within the scope of defense application. Instead, the design alternatives for light field displays in such context is provided.

Light field displays may vary a lot in terms of capabilities and technical properties; one could say that they come in "different shapes and sizes". Shape does not only refer to the aspect ratio of the screen of the display, but also to its actual physical shape. Recently, Holografika introduced a 3D light field LED wall,[1] which is an any-size, any-aspect, any-shape modular display that can be applied to any surface. It is a tileable solution, as the display can be arbitrarily composed of tile units to fit its purpose. Apart from physical dimensions and shape, the resolution values of light field displays and contents fundamentally affect the perceived quality and thus, the efficiency of the use case. From these parameters, angular resolution is to be highlighted, since it determines the smoothness of the parallax effect. Insufficient visualization quality for defense applications is simply unacceptable, since visual artefacts – such as the crosstalk effect – may distort the warfare-related information, which may lead to highly suboptimal tactical and strategic decisions.

From another practical – or rather, economical – perspective, light field displays are definitely among the most expensive visualization systems of our time. However, military expenditure – particularly in case of certain countries – can be, the least to say, quite high. According to the Stockholm International Peace Research Institute (SIPRI),[2] in 2020 alone, the world spent nearly 2,000 billion US dollars for this purpose. From this total sum, the United States of America spent 778 billion. As for the future, military expenditure is expected to rise, since, for example, due to the conflict in Ukraine – which is happening at the time of writing this paper – Germany recently announced a special fund of 100 billion Euros for the modernization of its military. Summa summarum, the modern military in general has always been known for investing in the utilization of cutting-edge technologies, and therefore, it would not be a surprise to witness a shift towards light field visualization in the upcoming years.

Still, as it has already been stated, such systems must serve their purpose well, and this can only be achieved if they are properly tailored to their respective use cases. Again, failure to do so may have severe consequences, particularly when it comes to battlespace visualization for high-level decision makers.

In this paper, we propose a range of potential technical solutions for 3D battlespace visualization on light field systems. We consider the suitability of existing commercial devices and the design of dedicated hardware. Within the scope of this paper, we address the requirements of three specific use cases: (i) real-time, time-sensitive 3D battlespace visualization for decision makers, (ii) reconnaissance and supervision of defense-related activities that are not time critical, and (iii) training and simulation. From the implementation archetypes of light field visualization technology, we focus on projection-based solutions.

The remainder of this paper is structured as follows: Section 2 briefly reviews the related work and the state-of-the-art solutions. Section 3 analyzes the use cases in terms of observer perspective and the required system FOV. Section 4 addresses the potential user interactions. Section 5 discusses the spatial and angular resolution of light field visualization in the investigated context. Section 6 introduces consideration regarding the parallax effect. Section 7 studies the suitability of current light field displays for battlespace visualization purposes and elaborates the potential benefits of dedicated systems. Section 8 concludes the paper.

2. RELATED WORK

At the time of writing this paper, a 3D light field battlespace visualization system already exists[*], developed by Avalon Holographics. The demonstration of the use case introduces a system with a squared-shaped screen that is parallel with the horizontal axis and thus should be viewed by looking down at it – similarly to a table with unfolded maps. The rendered concept exhibits capabilities of direct interaction via multiple interfaces on the sides of the dedicated device, and shows advanced functions (e.g., visualizing radar coverage) beyond rotating the view and changing its level of zoom. The human-computer interface (HCI) appears to be a conventional 2D digital panel, which is understandable, since having a light field HCI does not come with any apparent added benefit for this use case. The specific example shows the coordination of an aviation-assisted naval battle, and the context highlights the portability of the system (i.e., it appears to be located on the bridge of a naval vessel).

While the conceptual demo is indeed promising, unfortunately, no technical information is available regarding any practical implementation. Everything that appears in the demo is theoretically feasible; however, based on the conveyed information, nothing can really be assumed about its visualization quality. Beyond battlespace visualization, Hamilton *et al.*[3] from Avalon Holographics addressed the use cases of medical imaging, air traffic control, detection, training and design.

Creating such a system was also attempted by Zebra Imaging in the beginning of the past decade. The company also developed holographic maps that could be provided to military personnel prior to entering an area (e.g., a battle zone). In 2017, it was announced that the assets shall be sold to HoloTech Switzerland.

The HoloVizio HV640RC[4] was partially developed as a large-scale (screen diagonal over 1.8 m) battlespace visualization system. While it serves as a general-purpose light field display, one of its original purposes was to visualize military air traffic and potential air combat. Through glasses-free visualization, the respective distances and aircraft movement in the airspace could be perceived, along with the terrain and key entities on the ground. As a large-scale display, it was designed to serve as a central projection system for many individuals. Simultaneously, the airspace was monitored by conventional computer stations as well, typically with a single user. On a smaller scale, the HoloVizio 128WLD[5] was considered for a similar purpose – of course, using it as a central projection system was less evident due to its size (dimensions of conventional TV sets). However, such display may be more suitable for utilization at single-user stations.

In other works of the scientific literature, visualization quality and other vital components of viewer and user experience are evaluated. Adhikarla *et al.*[6] tested freehand gesture task performance on a projection-based light field display prototype. The work compares 2D and 3D HCIs on the same display. While the 2D HCI was still practically light field, the authors minimized the depth of the content to make it flat on the plane of the surface of the screen. The results indicate that less time is needed for task performance in case of a 2D HCI than a 3D one. The work of Tamboli *et al.*[7] addressed content orientation on light field displays. The experiment used a conventional controller to rotate the visualized objects, and found correlation between the spatial form of the object and user preference. Darukumalli *et al.*[8] investigated the level of zoom for static light field scenes. The works of Kara *et al.* studied display FOV,[9] spatial[10] and angular resolution[11] and the interdependencies between them,[12] and the viewing distance of use cases.[13–15] All of the research efforts above are highly relevant to the successful use-case-centric design and implementation of efficient light field battlespace systems.

[*]https://www.avalonholographics.com/use-cases/holographics-for-enhanced-battlespace-visualization

3. POINT OF VIEW AND FIELD OF VIEW

The first thing to consider regarding the investigated use cases is the number of simultaneous users. As it has already been stated earlier, light field displays can be viewed by many individuals simultaneously. However, not every single use case of light field visualization need to accommodate numerous viewers and users simultaneously. Therefore, the FOV of the display does not necessarily need to be impressively large. In other words, if a use case involves only one user, whose perspective is not expected to deviate much during the use of the system, then it is rather unnecessary and inefficient to provide visualization over a full 180-degree FOV.

During the use case of real-time, time-sensitive 3D battlespace visualization for decision makers, multiple simultaneous viewers are expected. As viewers need spatial separation, the FOV must be large enough to accommodate them. However, in such case, the choice of FOV also depends on the perspective of the viewers with respect to the screen. There are three main options: (i) the screen is vertical – which is analogous to the majority of display systems – (ii) the screen is horizontal – as in case of the "table" approach – or (iii) the screen is slanted – so basically it is both vertical and horizontal. If the screen is vertical, then a rather wide FOV is needed. This value is reasonable up until 160–165 degrees. First of all, research indicates[10] that FOV above 165 degrees does not provide added value to general passive use cases of light field visualization, and secondly, it is not practical for decision makers to view a battlespace system from those angles during a time-critical scenario. If the screen is slanted, then similar considerations apply. However, if the screen is horizontal, then it is expected that decision makers would stand close to the edge of the system. Therefore, a smaller FOV may be sufficient as well. Theoretically, an FOV of around 80–85 degrees should suffice if every viewer of the use case stands right next to the system. Yet, since we cannot make such assumption and since reasonable distances should be considered, an FOV of at least 110–120 degrees is required.

Reconnaissance and supervision are either performed by a single individual or multiple personnel. Since it is likely that the system is used by more than one person at a time, the design principles regarding the FOV are analogous to the previous use case. The lack of the time-sensitive nature of the use case does not affect the requirements towards FOV.

During training and simulation, it is more likely that the system is used by only one person. Of course, for example, there may be training events during which the previous use cases are simulated and thus, multiple simultaneous viewers must be accommodated. Let us assume a scenario with one user only. This could be, for instance, the station of a detection subsystem in a navy vessel. In such case, it is more adequate to have a display, the screen of which is either vertical or slanted. As the sole user of the station is expected to be sitting, a display FOV of 40–45 degrees may be perfectly suitable for the use case.

If the screen is aligned horizontally, then it is perfectly valid to have asymmetrical systems. Depending on the size of the screen, it may be the case that a portion of visualization is never observed by the users of the system. In essence, in case of a larger screen, it is completely impractical and difficult to imagine to have a user looking down at the center of the screen. Therefore, it is unnecessary to cast such rays. Technically, this means that a use-case-dedicated system could be designed with a "hole" in the middle of light field visualization.

Additionally, due to the angularly selective nature of light field displays, it is a possibility for a system to visualize one content in one direction, and a different one in another direction. If we assume a station with 2 individuals simultaneously using a single display system – one sitting on the left, the other one sitting on the right – then they could independently supervise two detection functions simultaneously; they look at the same map but see different information overlays. Furthermore, it is, in fact, possible to have two completely different contents visualized on the same display. Depending on the size of the FOV, visualization may be split into even more independent angular regions.

4. INTERACTION AND ENGAGEMENT

In case of the conventional battlespace visualization approach, it is common that decision makers move around the table to gain a different perspective of the situation. However, when the responsiveness is of key importance and the time of decision making may fundamentally affect the outcome of events, is such movement still practical or should digital perspective change (e.g., rotation along either axis, pan or zoom) be dominant? Furthermore, in case of the latter, should the system be controllable by multiple personnel?

If interaction only aims to change the perspective of the battlespace, then freehand control is an appropriate choice, as signified by Adhikarla *et al.*[16] However, if more complex actions are involved (e.g., adjusting or turning on or off the visualization of detection ranges), then 3D light field control HCIs are not advised, due to the additional cognitive load and thus extended task performance times.[6] A suitable alternative is to have either flat control panels or physical control interfaces (i.e., buttons, switches etc.).

3D HCIs could be utilized within use cases that are not time critical. Yet, at the time of this paper, no research efforts indicates that light field user interfaces could provide any specific advantage over conventional controls. Hybrid solutions (i.e., the combination of freehand and conventional controls) are suitable for real-time multi-personnel scenarios; however, in a single-user yet time-critical context, changing between the interfaces could result in more loss of time than in case of purely light field controls.

Regarding multi-user scenarios, it is a valid option to assign different interaction tasks to different individuals. In such case, tasks can be carried out simultaneously. Visualization parameters can also be altered by multiple users from multiple positions. For freehand control, this would necessitate additional sensors.

5. SPATIAL AND ANGULAR RESOLUTIONS

Spatial resolution and angular resolution are Key Performance Indicators (KPIs) of light field visualization.[17] Spatial resolution is responsible for the "sharpness" of visualization, while angular resolution determines the smoothness of the parallax effect. If spatial resolution is insufficient, then visualization is affected by blur. Note that the intensity of such blur is not uniform across the screen and that visualization is always the sharpest in the plane of the screen. If angular resolution is insufficient, then the adjacent perspectives of visualization may interfere with each other, resulting the crosstalk effect.

The scientific literature[10–12, 18–20] clearly indicates that degradation related to angular resolution may have a greater impact on the perceived quality of light field visualization than spatial resolution. However, it is important to highlight that research on spatial resolution primarily involved 3D objects. In case of battlespace visualization, it is likely that that the conveyed information includes texts and numbers. While the blur induced by insufficient spatial resolution is generally somewhat tolerable for rendered objects – particularly if the objects are without surface textures[10] – it may significantly degrade the efficiency of the use case if textual information is visualized. Misreading texts and numbers may have severe consequences in mission-critical contexts, but other relevant use cases may be affected as well. Furthermore, even if the visualized information is not misread, misinterpreted, the delay caused by data confirmation may negatively influence the performance of real-time, time-sensitive activities. Therefore, unlike in many other use cases of light field visualization, battlespace usage contexts should not accept compromises regarding spatial resolution.

Based on such statements, one may immediately think of 4K or 8K UHD resolutions, or resolutions even beyond 8K. However, a well-calibrated light field display may perform adequately on much lower resolutions as well. For instance, both the HoloVizio 722RC[†] and 80WLT[‡] have a spatial resolution of 1280×768. Additionally, the appropriate rendering of texts and numbers may also make battlespace visualization more resilient towards potential blur. Technically, it is possible for light field displays to render 2D contents, and there is absolutely no benefit of having texts and numbers rendered in 3D. It is, in fact, possible to combine 2D and 3D visualization in light field technology. It means that the 2D portion of the content is precisely the same from every perspective, hence, the light rays reaching the pupils of the observer do not have any binocular disparity. Furthermore, texts and numbers should be rendered in the plane of the screen in order to be as sharp as possible. In subjective studies with test participants, Kovacs *et al.*[18–20] addressed symbol recognition. However, according to the best knowledge of the authors, research on text and number readability is currently lacking.

In case of vertical and slanted screens, text orientation is a straightforward matter; it is analogous to conventional 2D displays. However, in case of horizontal displays, there are two possible approaches. One is that a single orientation is applied, which is either fixed or may be rotated. The other one is that text is made readable from every perspective. The obvious benefit of this approach is that every text may be read from any

[†]https://holografika.com/722rc/
[‡]https://holografika.com/80wlt/

viewing position. However, there are multiple technical drawbacks. First of all, adjacent views vary in terms of the visualized textual content, and therefore, the solution is more vulnerable to insufficient spatial resolution. Technically, the text in such case suffers "ghosting" artefacts. Secondly, fulfilling this property increases the requirements towards parallax. Not only that, but the angular change also complicates matters in terms of angular resolution.

Angular resolution is a vital KPI of light field visualization. When expressed in degrees, it defines the smallest angular change; the angle between two distinct adjacent light rays with respect to a given point on the screen. High angular resolution enables a smooth transition between perspectives of the continuous visualization within the FOV. In case of insufficient angular resolution, while the loss in the smoothness of the parallax does degrade the visual experience, the primary issue comes from the crosstalk effect, which, at specific extents, may make the content almost unrecognizable – especially if the content has a considerable depth. Since 3D battlespace visualization, similarly to medical application of light field technology, does not tolerate errors – particularly when decision makers are involved – there should be strict requirements regarding angular resolution. Based on the best practice in the industry and on the outputs of the scientific community, the bare minimum for light field battlespace visualization should be at least 1 degree. This value is adequate for training and defense activity supervision, whereas for mission-critical usage, at least 0.5 degrees is recommended.

The appropriate selection of angular resolution depends on other factors as well. If visualization aims to provide more depth – in order to assist situational awareness – then a better angular resolution is needed, since the more the content leaves the plane of the screen, the more susceptible it becomes to degradation. It is also implicitly affected by the size of the screen. In case of larger screens, it is more likely that viewers are situated farther away from the screen. In case of use-case-dedicated displays, if the expected viewing distance range is known, then the angular resolution may be chosen accordingly. As an example, if the screen is exceptionally large and it is thus viewed from greater distance, not even 0.5 degrees will suffice.

6. HORIZONTAL AND VERTICAL PARALLAX

In case of a horizontal-only parallax (HOP) light field display, if the screen is set in a traditional vertical alignment, then the change of content perspective can be observed when moving sideways, but changing viewing altitude does not result in a different perspective of the content. Reality is best represented by full-parallax (FP) displays, as they provide parallax along both axes.

The viewing perspective of the users is probably one of the most important factors in terms of parallax, and it is highly related to screen alignment. If we consider use cases of 3D battlespace visualization where the screen is vertical, then HOP displays may fully satisfy user requirements. On the other hand, the choice of parallax regarding slanted displays is much less straightforward. If the angle of the screen is below 45 degrees (i.e., closer to being vertical), then HOP displays may still be a reasonably utilized. However, for other slanted displays and horizontal screens, having FP may be advised.

In the future, it is expected that most use cases of light field visualization will rely on FP displays. This is, however, a somewhat distance future, as the consumer market has yet not been penetrated by light field displays in general. In fact, most researchers who work in the area of light field do not have access to light field displays, as they are not widely available to institutions. Furthermore, at the time of writing this paper, no commercial FP solution has been introduced yet.

With all this in mind, it is most likely that the first technological wave of light field battlespace systems will be HOP displays. Even if FP displays emerge, in a context where an individual is sitting at a station, HOP displays are sufficient due to the lack of change in the vertical perspective. In the industry, it is said that if observers can all simultaneously view the display from a line – standing or sitting next to each other – then HOP visualization is sufficient. In any other case, using an FP display is meaningful.

Additionally, on a technical level, creating and operating FP displays is an exceptional challenge. Compared to HOP displays, FP solutions require at least a hundred times more light rays. Such difference can increase the related costs drastically.

7. COMMERCIAL AND DEDICATED DISPLAYS

The paper now addresses the final question: Are commercial light field displays in general suitable to fill the role of a 3D battlespace system or is the design and implementation of dedicated displays necessary? Commercial displays narrow down the possible system architecture archetypes, as they all have vertically aligned screens, just like conventional 2D displays. Therefore, if the horizontal nature of the screen is a requirement, then a use-case-dedicated light field display needs to be created, such as the 3D battlespace visualization system of Avalon Holographics.

In terms of interaction, an advantage of dedicated systems is the possibility to embed control interfaces, particularly designed for the control functions. On the other hand, every commercial light field display may be arbitrarily extended by such interfaces. The only major constraint may be the fact that they are essentially operated by computers. However, if it is compatible with the use case context to have a dedicated control station (i.e., a computer), then using commercial light field displays for the purpose of battlespace visualization is an acceptable practical choice.

As for spatial and angular resolutions, the state-of-the-art commercial displays are able to produce the necessary resolution values. At the time of writing this paper, the scientific community has no data on the perceived quality of super resolution, which refers to a light ray density so high that a single point of the screen may address one pupil with two distinct rays. Therefore, super resolution enables viewers to focus on specific spatial portions of the visualized content. Without super resolution, viewers always focus on the plane of the screen. Once super resolution display systems become available, research should address the potential added value – particularly regarding situational awareness – and measure task performance. If the output of such research favors super resolution, then dedicated displays should definitely aim to provide such feature.

Regarding the parallax effect, HOP displays may be adequate for every use case of 3D battlespace visualization. If the screen of the display is vertically aligned and the use case does not typically involve vertical changes in the perspective of the viewer, then the utilization of FP displays are not necessary and commercial systems may fit the role well.

Another important consideration may be the physical properties of the state-of-the-art commercial light field displays. The high-end systems are typically large and heavy, and they tend to produce excessive heat. Of course, nobody would think to install a light field cinema on a naval vessel. In usage contexts, where the combination of size, weight, generated heat and visual performance of the displays is of key importance, dedicated systems may be more appropriate. In other environments, such as a command station in a building, commercial displays are usable as well. As an example for a commercial yet more compact, but still high-performance display, the HoloVizio 80WLT may fit an environment with spatial constraints. However, generally, constrained environments could benefit more from dedicated systems and modular displays.

Lastly, it should also be considered that battlespace visualization systems are expected to operate over extended periods of time. Therefore, in case of projection-based light field visualization, optical engines should be able to withstand 24/7 operation. Dedicated systems can be specially equipped with such in mind. Yet, according to experience in the industry, state-of-the-art commercial light field displays may endure operation over extended periods of time as well.

8. CONCLUSION

In this paper, we presented our work on light field battlespace visualization and defense applications. We conclude that most commercial HOP light field displays are suitable for 3D battlespace visualization if the use case is compatible with a vertical screen alignment, and there are no major constraints regarding total system size, weight, and heat generation. Additionally, a state-of-the-art display may also serve the purpose of light field battlespace visualization quite well if it is situated at a computer station. This is particularly applicable to the use cases of training and reconnaissance supervision. For real-time, time-critical use cases with multiple decision makers, greater dimensions for visualization space may be necessary, and visual quality needs to comply with the requirements towards spatial and angular resolution in order to assist the cognitive processes of the decision makers. Use-case-dedicated systems may be optimal for constrained environments and table-like, horizontally-aligned screens, and they also provide the option for specialized, embedded control interfaces.

Super resolution is relevant for use cases where the viewing distance is small; for large-scale solutions – and thus potentially greater viewing distances – super resolution is exceptionally difficult to achieve and its added value benefits the users less. Based on the amassed technological knowledge of the industry and the scientific community, super resolution may be practical up to a viewing distance of a meter, perhaps a meter and a half. As for FP displays, the required resources are definitely daunting, and it is not certain that such requirements shall be fully justified. Still, it is rightfully considered to be the next step in the evolution of light field imaging, due to its potential contribution to visual realism and immersion.

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REFERENCES

[1] Balogh, T., Barsi, A., Kara, P. A., Guindy, M., Simon, A., and Nagy, Z., "3D light field LED wall," in [*Digital Optical Technologies*], **11788**, International Society for Optics and Photonics (2021).

[2] Da Silva, D. L., Tian, N., and Marksteiner, A., "Trends in world military expenditure, 2020." SIPRI https://sipri.org/sites/default/files/2021-04/fs_2104_milex_0.pdf (2021).

[3] Hamilton, M., Butyn, T., and Baker, R., "Holographic Displays: Emerging Technologies and Use Cases in Defence Applications." https://www.sto.nato.int/publications/STO%20Meeting%20Proceedings/STO-MP-MSG-159/MP-MSG-159-08.pdf (2018).

[4] Agócs, T., Balogh, T., Forgács, T., Bettio, F., Gobbetti, E., Zanetti, G., and Bouvier, E., "A large scale interactive holographic display," in [*IEEE Virtual Reality Conference (VR 2006)*], 311–311, IEEE (2006).

[5] Balogh, T., Forgács, T., Agocs, T., Balet, O., Bouvier, E., Bettio, F., Gobbetti, E., and Zanetti, G., "A scalable hardware and software system for the holographic display of interactive graphics applications.," in [*Eurographics (Short Presentations)*], 109–112 (2005).

[6] Adhikarla, V. K., Jakus, G., and Sodnik, J., "Design and evaluation of freehand gesture interaction for light field display," in [*International Conference on Human-Computer Interaction*], 54–65, Springer (2015).

[7] Tamboli, R. R., Kara, P. A., Cserkaszky, A., Barsi, A., Martini, M. G., and Jana, S., "Canonical 3d object orientation for interactive light-field visualization," in [*Applications of Digital Image Processing XLI*], **10752**, 77–83, International Society for Optics and Photonics (2018).

[8] Darukumalli, S., Kara, P. A., Barsi, A., Martini, M. G., and Balogh, T., "Subjective quality assessment of zooming levels and image reconstructions based on region of interest for light field displays," in [*International Conference on 3D Imaging (IC3D)*], 1–6, IEEE (2016).

[9] Kara, P. A., Kovács, P. T., Martini, M. G., Barsi, A., Lackner, K., and Balogh, T., "From a different point of view: How the field of view of light field displays affects the willingness to pay and to use," in [*8th International Conference on Quality of Multimedia Experience (QoMEX)*], IEEE (2016).

[10] Kara, P. A., Kovacs, P. T., Martini, M. G., Barsi, A., Lackner, K., and Balogh, T., "Viva la resolution: The perceivable differences between image resolutions for light field displays," in [*5th ISCA/DEGA Workshop on Perceptual Quality of Systems (PQS)*], 107–111 (2016).

[11] Kara, P. A., Martini, M. G., Kovács, P. T., Imre, S., Barsi, A., Lackner, K., and Balogh, T., "Perceived quality of angular resolution for light field displays and the validity of subjective assessment," in [*International Conference on 3D Imaging (IC3D)*], 1–7 (2016).

[12] Kara, P. A., Cserkaszky, A., Barsi, A., Papp, T., Martini, M. G., and Bokor, L., "The interdependence of spatial and angular resolution in the quality of experience of light field visualization," in [*International Conference on 3D Immersion (IC3D)*], 1–8 (2017).

[13] Kara, P. A., Tamboli, R. R., Cserkaszky, A., Barsi, A., Simon, A., Kusz, A., Bokor, L., and Martini, M. G., "Objective and subjective assessment of binocular disparity for projection-based light field displays," in [*International Conference on 3D Immersion (IC3D)*], 1–8 (2019).

[14] Kara, P. A., Guindy, M., Balogh, T., and Simon, A., "The perceptually-supported and the subjectively-preferred viewing distance of projection-based light field displays," in [*International Conference on 3D Immersion (IC3D)*], 1–8, IEEE (2021).

[15] Kara, P. A., Barsi, A., Tamboli, R. R., Guindy, M., Martini, M. G., Balogh, T., and Simon, A., "Recommendations on the viewing distance of light field displays," in [*Digital Optical Technologies 2021*], **11788**, International Society for Optics and Photonics (2021).

[16] Adhikarla, V. K., Woźniak, P., Barsi, A., Singhal, D., Kovács, P. T., and Balogh, T., "Freehand interaction with large-scale 3D map data," in [*3DTV-Conference: The True Vision-Capture, Transmission and Display of 3D Video (3DTV-CON)*], 1–4, IEEE (2014).

[17] Kara, P. A., Tamboli, R. R., Doronin, O., Cserkaszky, A., Barsi, A., Nagy, Z., Martini, M. G., and Simon, A., "The key performance indicators of projection-based light field visualization," *Journal of Information Display* (2019).

[18] Kovács, P. T., Lackner, K., Barsi, A., Balázs, Á., Boev, A., Bregović, R., and Gotchev, A., "Measurement of perceived spatial resolution in 3D light-field displays," in [*International Conference on Image Processing*], 768–772, IEEE (2014).

[19] Kovács, P. T., Boev, A., Bregović, R., and Gotchev, A., "Quality measurements of 3D light-field displays," in [*Eighth International Workshop on Video Processing and Quality Metrics for Consumer Electronics*], 1–6 (2014).

[20] Kovács, P. T., Bregović, R., Boev, A., Barsi, A., and Gotchev, A., "Quantifying spatial and angular resolution of light-field 3-D displays," *IEEE Journal of Selected Topics in Signal Processing* **11**(7), 1213–1222 (2017).