Holographic Displays: Emerging Technologies and Use Cases in Defence Applications

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ABSTRACT

In recent years, Head Mounted Display (HMD) Virtual Reality (VR) technologies have attracted significant attention, promising to offer new immersive experiences. In contrast, the theory behind stand-alone holographic displays has been understood for many years, yet a usable production device has yet to be realized. Recently, several new holographic light field display players have emerged. These displays avoid usability issues of HMDs, by providing a collaborative, social environment that avoids the isolation of the user from their environment and other users.

We review emerging holographic display technologies and their capabilities. We also review existing literature which suggests that such displays can improve human performance in visualization tasks by decreasing cognitive load. This results in increased task effectiveness and improved situational awareness in a wide variety of contexts.

Finally, we describe several defence-related use cases where holographic display technology has the potential to offer substantial usability improvements. These use cases include battlespace visualization, medical imaging, training and simulation and computer aided design (CAD). We show that as implementations of these technologies emerge, the defence community will be early adopters and have many opportunities to leverage them for tactical and/or strategic advantage, to improve the training and the ultimate effectiveness of warfighters.

1.0 INTRODUCTION

Existing two-dimensional (2D) flat panel displays have made continuous advances over the years, rapidly decreasing in form factor while steadily increasing in image resolution, color reproduction and dynamic range capabilities. As conventional 2D displays have become smaller, lighter and denser, an industry promoting Head Mounted Display (HMD) Virtual Reality (VR) technologies has arisen. Related technology has also become available in the form of Augmented or Mixed Reality (AR /MR), which combines the natural light field with an additional digital light overlay.

These near-to-eye worn displays represent a major improvement, and offer some new and compelling user experiences not available with conventional display technology. In the barest form of VR HMD, each eye is presented with a different view of a virtual scene, allowing for stereoscopic depth cues, thus enhancing sense of depth for users. The head-tracking capability built into these HMDs additionally allows for a realistic sense of scene shift (motion parallax) as the user moves their head. These capabilities can present a significantly enhanced sense of immersion that users find compelling and visceral. However, HMDs continue to suffer from some major flaws:

- People do not really want to wear screens, and will only tolerate this in a significant way (i.e. mass market) if these screens are incredibly light and comfortable, similar to eyeglasses today.
- The technological challenges to reach this form factor while creating a meaningful user experience are massive, and currently under-reported.
- These technologies also have perceptual issues that cause user discomfort, such as accommodation-convergence (AC) conflict issues, that may be difficult to resolve.
- Immersive VR technologies have a very important additional problem, in that the body's vestibular system (inner ear) that controls balance responds badly to perceiving motion visually without the accompanying vestibular movement. It is unclear how this problem can ever be resolved.

Another hindering aspect of VR HMDs is the lack of social experience that the isolated head-worn device provides. In battlespace and other critical decision-making applications, decisive action based on available data is ideally conducted in an environment where eye-contact and bodily cues allow a team to rapidly communicate and arrive confidently at the right decision. Though AR technology may reduce the isolation of VR, the relatively small field of view and still large form factors of existing technologies suggest that alternatives based on stand-alone displays must be considered.

In contrast, it has been theorized that a potentially superior experience of 3D immersion can be provided by holographic displays. If realized, these displays can avoid usability issues of HMDs by providing a collaborative social environment that avoids the isolation of the user from their environment and other users via a single, shared display experience - just like the vast majority of displays used today. The theory behind stand-alone holographic displays has been understood for many years, as holographic prints have been demonstrated to provide a compelling immersive still frame experience [1], [2]. However, a usable production device for dynamic video content has yet to be realized, as implementing the technology requires fundamental technological advances on several fronts.

In this paper, we give an overall review of existing 3D display technologies and their capabilities. This includes an overview of existing 3D display design approaches. We further discuss the landscape of next generation 3D displays and how technology will progress to allow for usable holographic displays in the near future. We also review existing literature which suggests that such displays can improve human performance in visualization tasks by decreasing cognitive load.

Finally, we describe several defence-related use cases where holographic display technology has the potential to offer substantial usability improvements. These use cases include battlespace visualization, medical imaging, air traffic control, sonar and radar, training and simulation and computer-aided design (CAD). We show that as implementations of these technologies emerge, the defence community will be early adopters and have many opportunities to leverage them for tactical and/or strategic advantage, to improve the training and ultimate effectiveness of warfighters.

2.0 PERCEPTUAL ASPECTS OF 3D DISPLAYS

In essence, a quality 3D display must somehow reproduce, as faithfully as possible, the field of radiance that human eyes encounter when viewing typical objects in the real world. In a conventional 2D display, each pixel can be controlled in terms of its color and intensity but has no variable control over the direction of light, being based on a fixed angular light distribution pattern that defines its field of view. Existing 2D displays, despite their impressive advances, fall short of providing a full immersive experience because they lack several very critical perceptual cues associated with realistic 3D perception, such as stereoscopic, focus and parallax cues.

A quality 3D display would replicate the field of light that passes through the display's viewing plane, including the directional component. This model of a 3D display is known as a light field display. The term "light field" at a fundamental level refers to a function describing the amount of light flowing in every direction through points in space, free of occlusions. Therefore, a light field represents radiance as a function of position and direction of light in free space. More formally, a light field can also be understood as a mapping from a four-dimensional space to a single RGB color [3], [4]. The four dimensions include the vertical and horizontal dimensions of the display and two dimensions describing the directional components of the light field. That is to say, the light field display casts RGB light rays outwards in a parameterized field-of-view towards the observer(s). A light field (LF) is defined as the function: LF: $(x,y,u,v) \rightarrow (R,G,B)$.

A fully implemented 3D light field display will replicate this field of light based on its ability to represent both angular and spatial variation. As a result of these extra dimensions of optical control, a light field display provides additional perceptual cues not present in a 2D display, including:

- Focus (accommodation and retinal blur)
- Convergence
- Motion parallax
- Binocular disparity

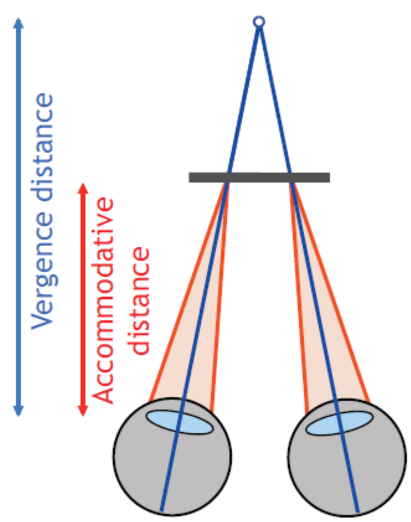

Figure 1-1: Accommodation-convergence conflict [5].

It is well known that existing autostereoscopic displays suffer from the negative effects of the accommodation-convergence (AC) conflict [6] (Figure 1-1). A mismatch in the eyes between convergence distance and accommodation (focus) distance is caused by limited view displays due to a lack of focus cues. This has been experimentally shown to induce physical strain and fatigue in viewers [6]. A densely-sampled light field in theory provides blur and accommodation cues, at least within a certain range of distance from the display surface. There is also significant evidence to suggest that incorrect focus cues (blur and accommodation) can alter shape and scene perception and limit visual performance, in addition to causing viewer discomfort [5], [7].

Takaki [8] experimentally demonstrated the AC-conflict for a particular display design. One resulting interpretation of these results is that convergence and accommodation appear to become mismatched most significantly when viewing objects beyond the depth of field of the display. Takaki makes the inference that a display must meet the super multi-view condition, which states that at least two views per eye must be provided by the display. This can effectively be achieved by requiring between 0.1--0.3 degrees of viewing angle per view when the viewer is assumed to be at a typical (60 cm) viewing distance from the display. Despite this insightful data, it is still reported to be an open question as to precisely how many views or what degree of angular resolution is required for a light field display to reduce the negative effects of the AC conflict [9]. However, what is clear is that existing light field displays do not appear to achieve enough angular resolution to alleviate these AC conflict issues.

In theory, by providing these additional cues over a 2D display, once a light field display reaches a certain resolution and quality threshold, what is viewed through it should be indistinguishable from reality. This would never occur with a 2D display, since it fundamentally cannot represent these important perceptual cues. A test to determine if a display meets this "window to the world" criteria, known as the 3D Turing Test [10], has been formulated: “Can you distinguish the 3D scene geometry you perceive from an advanced display from the geometry you perceive when viewing the real world?" [7]. The display passes the 3D Turing Test if the viewer cannot distinguish the display from reality.

In practice, it will be some time before any display will pass this test, based on several factors. One key factor is the degree to which objects at depth become blurry. In existing 3D displays and even in theoretically improved displays, light field displays exhibit a limitation in terms of how well objects that exist at depth from the display plane can be represented. Zwicker *et. al* [11] presented a framework to calculate the maximum depth of field of a 3D display, based on applying fundamentals of sampling theory into the multidimensional domain of a four dimensional light field image. The practical effect of this phenomenon is that as objects appear at distances far from (either in front or beyond) the display plane, they become blurry as the effective resolution of the display decreases. The practical consequence here appears to be that in order to represent objects at depth with the same resolution as objects that appear close to the display plane, significant angular resolution is required. In the near term, 3D displays can work within these limitations by limiting viewing depth of objects or by using scaling or billboarding techniques [12].

In the longer term, increasing angular resolution of 3D displays presents many technological challenges. Display optics must advance to be able to resolve and narrowly direct light in many discrete directions without significant distortions. The pixels and corresponding control circuitry that generate this light must be significantly smaller in order to achieve greater density, and the total number of pixels must increase dramatically. Moreover, the raw data volumes required to produce high frame rate video that drives an entire light field display will necessitate new solutions for data transmission over both short distances (e.g. computer to display) and longer distances (e.g. computer to computer over wide area networks).

3.0 REVIEW OF EXISTING 3D DISPLAYS

In this section, we give an overview of past approaches to implementing 3D displays. In each case, we describe why the approach fails to produce a usable display based on either fundamental limits or technological shortfalls. The class of displays that we consider here are group viewing displays, in that multiple users may view the display within some viewing region which would typically be specified by the display's field of view. Single viewer 3D displays which track the viewing position of an observer and tailor light output to this particular perspective do exist [13], but lack the immediate ability to provide a collaborative social experience, which is key in a number of application areas.

3.1 Wave Optics

A holographic display design operating at a scale where the wave nature of light is relevant has been studied as a potential design platform [14]. A traditional hologram works by recording both the amplitude and phase of the fringe pattern that is produced by the interference of the object and reference light beams onto a photographic film. The object beam is the reflected light that occurs when a portion of the reference beam is split and projected on to the object, while the reference beam is a collimated light beam generated from a coherent light source like a laser. This interference pattern can also be generated using a computer by modeling this object-reference beam interaction and the resulting fringe pattern can be output to a spatial light modulator (SLM) for object reconstruction. Existing wave optics approaches show some impressive results, but still suffer from severe limitations in terms of field of view and have rendering challenges required in terms of providing a high frame rate holographic video signal [15].

Wave optics designs, though showing future promise, face more immediate challenges than light field models, which are simpler both optically and computationally. In terms of human perception of objects by light, a geometric propagation model provides a sufficient level of description to cover relevant display-related perceptual phenomena. Thus, a light field display with sufficient spatio-angular resolution still has all the desired perceptual properties of a holographic display based on wave optics principles, such as stereoscopic, motion parallax and focus cues.

3.2 Integral Imaging

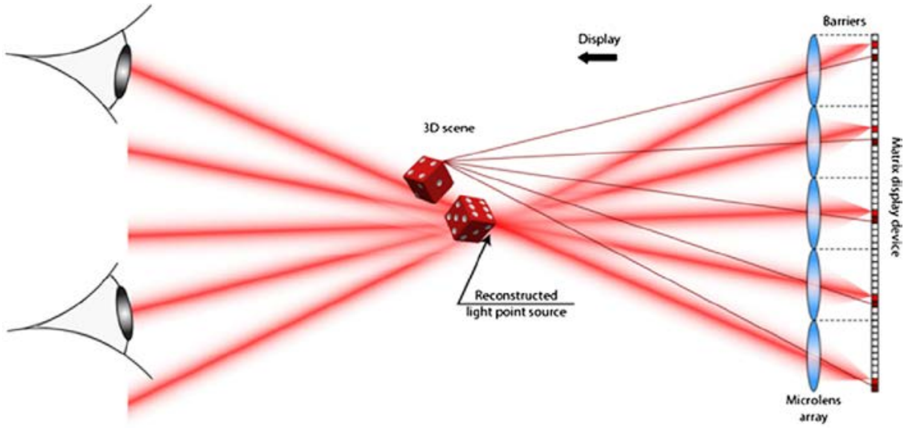

Figure 1-2: Schematic of an integral imaging display [16].

One type of light field display design uses arrays of microlenses over groups of light emitters in order to give the light from each pixel a specific, distinct direction. This is known as integral imaging and is actually a very old idea first proposed in the early 1900s [17]. There have been many integral imaging displays demonstrated in the literature [18], realized by placing microlens arrays over standard displays (Figure 1-2). Ostendo Technologies has presented an integral imaging approach to making a 3D light field display [19]. This effort differs in that they are using a custom underlying display with some novel properties. Their underlying displays have pixels much smaller than those found on a typical 2D display (10 microns); even smaller than those found in high density smartphones. However, these displays are very small and require tiling in order to create a usable display. Zebra Imaging (now FOVI 3D) [20] have also presented an integral imaging style display based on tiling of microdisplays with added lens optics. Both these tiled displays exhibit significant visual artifacts due to tile seams and optical leakage, making them unusable in many practical applications.

The main limitation of integral imaging designs is that there is an inherent tradeoff between spatial and angular resolution, assuming a fixed underlying pixel size and number of pixels. That is, as the microlenses are made bigger, more pixels can fit under the lens to provide greater angular resolution, but at the expense of spatial resolution. The main means to overcome this is to use smaller pixels; however, current technology limits for glass panel manufacturing use relatively large pixels, which do not support a sufficient combination of spatial and angular resolutions. It also appears that optics impose serious limits on these types of displays. Microlenses cannot provide a field of view greater than approximately 40 degrees (due to total internal reflection) unless stacked lens designs are employed; in such cases up to 90 degrees has been reported, as in the case of the Zebra display [20]. It is worth noting that a large amount of rendering architecture accompanies the Zebra display and its successor at FOVI 3D, due to the significant numbers of pixels that must be rendered.

Even with the relatively good angular resolutions exhibited by the microdisplay-based approaches, it appears to still offer a fairly small depth of field, showing noticeable blur at a shallow depth into the scene (See Figure 1-3). Smaller pixel technology (approaching sub-micron sub-pixel sizes) and optics which increase the achievable field of view without introducing artifacts are required to make this approach work for usable light field displays.

3.3 Diffraction-Based Optics

Other designs based on modification to existing 2D displays have also been demonstrated. LEIA has implemented a 3D display design that allows directional control of individual pixels on existing LCD displays, in order to create a light field [21]. This is achieved with commercially available liquid crystal technology, with a diffractive back light solution (See Figure 1-4). This technique is impressively flexible, since each grating can be easily and fairly accurately tuned to an arbitrary direction by varying the direction and frequency of the diffraction gratings. However, because these utilize existing LCD screens with their restrictions on the number and size of pixels available, very limited angular resolution is all that is possible. Even if smaller pixels were available, these gratings only work when their size is greater than the wavelength of the light being directed, thus limiting this technology's future scaling to smaller pixels to achieve greater angular resolution.

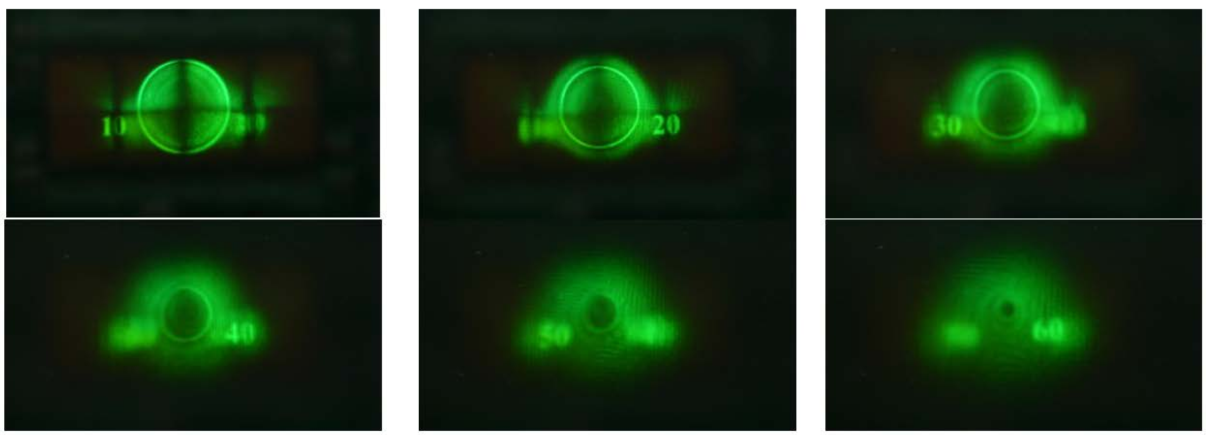

Figure 1-3: Depth of field limitation of a light field display [19]

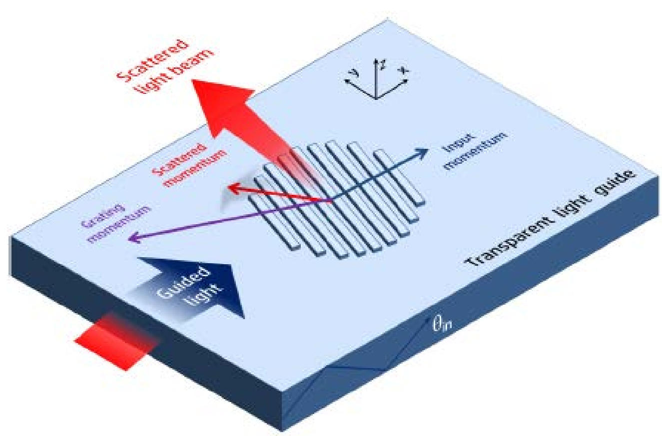

Figure 1-4: LEIA directional pixel [21].

3.4 Compressive

Multi-layered light field displays based on stacking optics and multiple light modulators (optionally with a directional backlight) have also been demonstrated [22]. This approach is also referred to as the compressive display approach. Both spatial and temporal modulation can be used within individual layers. These displays move the complexity of directing light to computation from optics. The superposition of light created spatially and temporally by the layers is used to produce the desired output light field, rather than through individual pixels mapped strictly to a single direction, as in most other approaches. The advantage of this technique is that it is able to achieve a greater directional resolution than the total number of pixels through the superposition principle, thus its “compressive” label. This allows for overcoming the inherent spatio-angular tradeoff of integral imaging. However, this comes with the significant cost of computing the modulation patterns for the individual layers based on the desired output light field, which would be infeasible for interactive rendering at this time. This approach is fine for static content, however, as the precomputation would represent a one-time cost.

3.5 Volumetric

Non-compressive layered displays based on additive (as opposed to multiplicative in the compressive approach) layers have also been created. These displays can create a high quality 3D image that provides accommodation and full parallax cues. However, the additive nature of the layers means that occlusion relationships are not properly rendered, since overlapping objects are represented as semi-transparent objects due to the additive nature of the layer blending. In other words, the display itself has constraints in terms of which light fields can be presented. The semi-transparent blending can be useful in some medical visualization or other 3D field visualizations, as these typically can be based on volumetric rendering.

Smalley et. al. [23] describe a highly novel volumetric display approach, based on photoretic-trap called an Optical Trap Display. The initial demonstration is impressive in that a very large field of view is exhibited due to the ability to use photoretic-trap to redirect light, though does not appear to be able to yet represent occlusion as with many other volumetric approaches. Also, the presented design is not expected to perform well outdoors or under conditions with uncontrolled air flow.

3.6 Projector-Based Displays

Another interesting approach to light field displays involves the use of many small projectors. Holografika has a commercially available Holovizio product that uses a projector-based design [24]. Their screens have been scaled up to large sizes (3m) and use up to 80 projectors. However, in the Holografika displays, the physical footprint of the display required to accommodate the physical size and arrangement of projectors appears to be much larger than that of modern flat-panel displays, and the 3D experience is limited to just horizontal-only parallax without use of glasses or tracking technology (Figure 1-5). Debevec's visual computing group at ICT designed a similar projector based display specifically for facial rendering, providing high angular resolution of 1.66 degrees between views, which they claim provides better quality than that of Holografika [25]. Third Dimension Technologies have also created horizontal-only parallax systems using off-the-shelf projectors [26]. In all cases, it appears that more than 20 video outputs are required to drive the displays. Due to the still limited angular resolution, these displays exhibit a small usable volume or effective DOF and horizontal-only parallax. There are no obvious inherent physical limitations which prevent one from applying similar principles to create a full-parallax projector based display; however, a much larger number of projectors would be required to provide similar quality, thus creating additional challenges in terms of how to render and/or deliver pixels at such enormous throughputs, in addition to the basic spatial logistics of assembling these many projectors into a confined space.

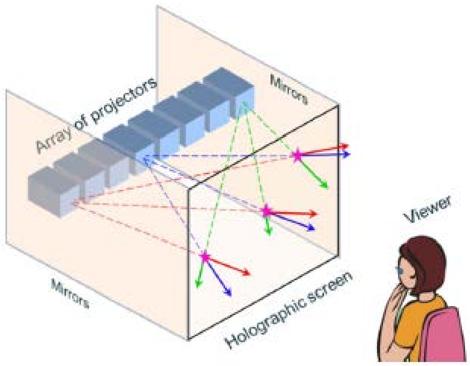

Figure 1-5: Projector array horizontal-only parallax light field display [27].

4.0 NEXT GENERATION DISPLAYS

Multiple light field display designs for group viewing have been proposed to date. None of these have yet provided a usable display, due to either not creating a full light field, having insufficient angular resolution or excessive display artifacts. Even if these issues could be addressed, effective group viewing ideally requires a display to have a large field of view, whereas existing displays come up against technological limits in the optics. Additionally, displays having theoretically adequate resolution have content delivery requirements in terms of bandwidth and rendering that significantly exceed the capabilities of existing technologies. For interactive computer graphics, rendering light field images of the sizes required at video frame rates poses significant challenges. Similarly, producing and streaming light field image content captured from the real world will pose transmission bandwidth limits. It is clear that a working display solution requires innovations across multiple parts of the content delivery and display systems.

It can be difficult to compare specifications and capabilities of holographic displays. With so many different parameters and trade-offs to consider, boiling down to simple comparison terms is challenging. Ideally, something akin to a space bandwidth product would be a good measure of display fidelity and capabilities, but this can be hard to assess. As described previously, one key element that impacts the visual quality of a display is the underlying pixel density, because this ultimately determines how much light information can be generated from a given area of display surface (assuming sufficient optics among all variants). Thus, a first-order comparison of display types can be made using the Pixel-Per-Inch (PPI) density of the underlying display. The table below compares existing displays and some known next-generation targets:

Table 1-1: Pixel densities in existing 3D displays

Vendor	Name	PPI (Pixels Per Inch) (approx. / est.)
Looking Glass	Standard	400
Leia3D		700-800

Ostendo Technologies	QPI	2,200
FoVI 3D	DK2	2,600
Light Field Lab	R150MP	2,600
Avalon Holographics	OLED Prototype	2,600
Avalon Holographics	Commercial Target	12,000

One key aspect in creating better light field displays is increasing pixel density. It is not strictly size that presents process challenges in making smaller pixels, as semiconductor processes with feature sizes of 7nm are currently ramping into mass production. Semiconductor chips, however, are much smaller than flat-panel displays and thus different materials and tooling are involved, requiring their own unique processes which present challenges in terms of current technology. Promising initial work has shown that photolithography may present a path to creating smaller OLED panels with high pixel density that will also be scalable beyond silicon based microdisplays and onto flat panel display technology [28] [29] [30].

High-throughput display simulation technology has been developed to confirm which spatial and angular resolution configurations can offer a high quality display across a wide range of possible content [31] [32] [33] [34], in a less expensive way than printed holograms could. However, these simulations and the resulting display quality shown rest on certain assumptions about specific performance of the optical system which is directing light rays appropriately from an underlying dense pixel array. Next generation optical systems will be required to direct light from smaller and smaller pixels into tighter angular beams without introducing significant losses. This will likely require careful optical design of spectral characteristics, employing spectral narrowing strategically to achieve the targeted light direction capability [35]. The other major challenge here is how to achieve an optical system which can achieve a large field of view, allowing for the most effective group viewing experience. Many promising optical technologies appear poised to tackle these challenges, with one example being work done on metamaterials and optics [36].

4.1 Light Field Rendering and Transmission

As an additional challenge, a light field display which provides the desired user experience poses enormous bandwidth and processing requirements, particularly in comparison to even the highest quality 2D displays available today. In raw terms, these bandwidth requirements appear to easily exceed what current technology can provide. The next future standard for consumer video is 8K Ultra High-Def (UHD), which provides only 33.1 megapixels per display, whereas we suggest that the minimal requirements for a usable light field display mean having at least hundreds of millions of pixels, with 10s of gigapixel displays easily anticipated in the future. In order to provide video and interactive content, this would imply a need for massive increases in data transmission capabilities, significantly improved light field CODECs, and advances in light field rendering algorithms and graphics hardware.

Based on an extensive review of literature, existing systems have not performed at real-time rates while delivering content at the targeted resolution and quality. It is clear that a new data transmission CODEC combined with novel hardware design must be developed in order to provide a 3D display that can be driven with interactive 3D content. The development of a rendering system that drives a usable light field display with interactive content is essential to make the display effective in many application areas. Though the bandwidth requirements appear to be orders of magnitude beyond existing technologies, there remains reason for optimism. Light fields have significant redundancy. Though anecdotal, it seems intuitive in many scenes that the image formed from all the unique directional intensities represented at a single point on a light field display differs very slightly from neighboring images. This redundancy is described in the literature under plenoptic sampling theory [37].

Within the literature, there have been several light field CODECs proposed and investigated. One category of compression techniques is based on having the entire light field data set, then processing it to reduce redundancy and produce a compressed representation. Many of these techniques are based on treating the set of elemental images as a video sequence and exploiting redundancy using standard video coding techniques [38]. Multiview specializations of compression standards are able to exploit redundancy between elemental images to achieve better compression rates, but at the expense of more intensive processing [39]. These techniques either do not achieve a sufficient compression ratio or, if a good ratio is achieved, are such that encoding and decoding processes are far beyond real-time rates. The chief issue with these approaches is that in order to encode the entire light field, it is assumed that it must exist in storage somewhere (presumably disk or in memory) before being encoded. For displays with 10s-100s of billions of pixels, the sheer size of this representation and reading it from the storage medium would introduce excessive latency.

Another category of approaches is based on using the *a priori* physical properties of a light field in order to identify redundancies in the data. These redundancies can be used to simply discard what is not needed, rather than performing computationally complex data transforms in order to identify information to discard. Piao and Yan [40] describe an approach based on discarding elemental images, based on the observation that elemental images representing neighboring points in space contain significant overlapped information. However, they do not utilize depth map information associated with each elemental image. A similar interesting approach was proposed by Graziosi *et al.* (Ostendo Technologies Inc.) [41], [42]. This method essentially equates the rendering process with the initial encoding process. Through this, one is able to avoid producing all elemental images and only produce the number needed to reconstruct the light field without any loss of information. However, the technique as presented seems to only work well for a single object that is far from the screen; in the worst-case, with multiple overlapping objects and many close to the screen, this technique would essentially just fall back on the H.264/AVC style encoding.

To overcome all of these issues, several technological barriers must be addressed in terms of display input bandwidth, optical control and scalable nanoscale fabrication. Custom high bandwidth transmission hardware combined with efficient CODECs amenable to real-time computation and interactive content must be developed to drive massive amounts of pixel data into these displays. Novel optical structures which improve upon existing refractive, microlens-based approaches must be developed to provide a large FOV display which maintains high quality for collaborative group applications. For the underlying foundation of pixels and driving circuits, nanoscale fabrication processes must be developed and optimized to facilitate efficient production of high-quality displays.

5.0 BENEFITS OF 3D DISPLAYS

The experience promised by light field displays is that of greater realism and immersiveness in virtual and real worlds. They will inevitably have a significant "wow" factor, after so many years of flat 2D displays and the existing mediocre 3D display efforts. Beyond this initial viewer amazement, however, there is a significant body of evidence that the extra information provided to a viewer through a light field display can have measurable benefits in terms of the usefulness of the display in various applications. We review the body of work which suggests that light field displays, and the additional perceptual cues provided can result in improved user performance in terms of various data visualization tasks.

In the information age, the large amounts of data produced potentially contain enormous amounts of valuable knowledge. It is well-known that a large portion of the human brain is dedicated to visual processing, with vision being the most developed human sensing system. The promise of the field of data visualization is that by making data visual, the enormous visual processing capabilities of the human brain can be exploited in order to increase human understanding of data.

Given the advent of powerful computer graphics acceleration hardware (GPUs), large 3D datasets can be rapidly rendered into 2D images for monoscopic displays. Despite the promises of visualization, 3D renderings of large datasets can still present problems to users. In various contexts, studies have shown that 3D datasets rendered to monoscopic images can increase cognitive loading; in particular, that their effectiveness seems limited to people with high spatial ability [43]. Other works have shown that physical visualizations of objects can improve a user's efficiency at information retrieval tasks [44] over that of 3D projections onto a 2D display.

Given that a high-quality light field display should present essentially the same light to an observer as a real physical object, it seems reasonable to hypothesize that it should provide similar benefits for visualizations as real world objects. Early studies showed the effectiveness of 3D volumetric and stereoscopic displays in specialized visualized tasks associated with air traffic controllers [45].The work reports that tasks requiring integration and prediction of moving three dimensional elements (e.g. collision prediction) seemed to benefit most from 3D displays. It is worth noting that these tasks exhibit a significant spatial cognition component, similar to planning and control of military missions and medical procedure planning, where similar spatial-temporal prediction capabilities are required.

Several studies based on user performance in visual tasks on printed holograms have been performed, showing positive results. Furhmann *et al*. [46] presented results showing that SWAT team members performed better in terms of route planning tasks with the use of printed holograms when compared to conventional 2D maps and imagery. Further studies augmented these results by collecting eye-tracking data [47]. Hackett [48] performed studies to determine if full-color printed holograms would give an advantage in anatomy education over conventional text book images. The results showed that the hologram images resulted in less cognitive load, suggesting usefulness in anatomical learning over flat 2D images of 3D anatomical objects. A further medical-based study proposed by Goldiez et al. [49] aims to study printed holograms of anatomy while also varying hologram parameters such as color or monochrome, contrast ratio, and polygon density, with results forthcoming.

Another body of work has considered the benefit of HMDs for VR/AR in terms of reducing cognitive load for data visualization and interpretation tasks. Though currently lacking in focus cues, AR/VR HMDs at a base-level provide stereoscopic and motion parallax cues which are not present in conventional 2D displays but are provided by light field displays. Binocular displays themselves without head-motion driven parallax have been shown to improve users' spatial perception and 3D object recognition [50]. Wismer *et al.* [51] performed fNIRS imaging of test subjects' brains in order to image neurological activity during visualization workload using physical models and models presented in VR. The results suggested that models viewed in VR provided similar measures of mental workload based on measured neurological activity as physical models, supporting the idea that VR can reduce cognitive workload relative to conventional 2D imagery. Several studies have focused on perception of volume rendered data, a technique that is highly utilized in medical visualization whereby density fields are visualized as cloud-like objects with variable transparency [52]. This representation offers an additional dimension beyond opaque surface representation, but can present significant perceptual challenges.

Boucheny *et al.* [52] showed that motion parallax helps disambiguate spatial relationships in volume rendering. Cho *et al.* [53] showed that VR display viewing of volume rendered data showed benefits over 2D display viewing, largely because of the ability of additional stereoscopy and head-coupled motion to disambiguate spatial relationships, particularly depth ordering, with both cues having measurable benefits.

Despite optimism for the benefits of 3D light field displays based on existing research, studies fully verifying these benefits on actual light field displays have not been reported, since existing displays have significant quality issues that interfere with perception. If other displays that overcome these issues exist, they have not been publicly released. When displays of sufficient quality do exist, it is proposed that comprehensive user studies should be performed in order to verify the hypothesis that light field based 3D representations will in general decrease the user's cognitive load when visualizing, interpreting and learning from complex datasets. It is worth noting that an orthogonal variable involved in visualization is the actual mapping used to produce images from given multi-dimensional data. Results such as those related to graph visualization (Kwon *et al.* [54]) suggest that visualization mappings of data to images that work well in immersive environments are different than those meant for traditional 2D displays. Using light field displays most effectively may also involve considering new visual mappings that were not previously useful in 2D or stereoscopic 3D displays and will form an additional branch of research required to embrace these displays in real world applications.

6.0 REVIEW OF USE CASES

We review a selection of applications of relevance to the defence community. All applications reviewed involve visualization of complex datasets, which are typically produced at great cost, and often require fast, efficient decision making. Thus, maximizing the information gained is key to maximizing value in the data. In all cases, the complex datasets, when visualized conventionally with 2D displays, appear to present significant cognitive load to human observers. Moreover, in most cases the insights contained in the data have a group component, in that the information that can be gleaned must either be efficiently disseminated to others, or the actual act of gleaning knowledge is itself a social, collaborative activity. These are requirements that cannot be currently met with HMDs. Thus, a standalone 3D display which provides light to the eyes as experienced naturally in the real world, reducing cognitive load while also providing the capability for multiple collaborative viewers, represents a next generation tool for use in these application areas.

Holographic displays have applications in many areas; in fact, most visualization scenarios include cases where true 3D representations can improve the user experience. However, this report focuses primarily on Defence-oriented applications. The authors have engaged extensively with members of the Canadian and US Armed Forces, and while this is by no means a complete list of the wide variety of the identified potential use cases, some of the most common cases are described below.

6.1 Battlespace Visualization

Battlespace Awareness (BA) and establishing a Common Operating Picture (COP) are some of the most critical operational objectives for warfighters, particularly for command staff and senior officers responsible for executive decisions and both strategic and tactical planning. For years, and often to this day, these functions have been supported by technologies as simple as paper maps with push-pins and verbal communications from the field. Modern warfare and equipment offer a tremendous amount of raw data to draw from - but filtering this data and presenting it as efficiently as possible without overwhelming the user is an ever-present challenge. Optimizing the presentation of this data is ultimately about managing the cognitive load on users. As discussed previously, holographic visuals can help by reducing the cognitive load for interpreting a given amount of data, or conversely communicating more information more efficiently than is possible on a 2D display.

A battlespace visualization application for Command and Control (C2) is the most commonly identified use case for holographic displays in all branches of the forces. Some of the first R&D in this area was sponsored by the Defence Advanced Research Projects Agency (DARPA) and the US Air Force Research Lab (AFRL), and interest in a tool to efficiently represent the spatial relationships between Space, Air, Land, Sea, and Cyber assets remains strong [20].

6.2 Medical Imaging

Medical practitioners are another group that has for years identified true 3D holographic displays as a valuable tool in several areas: high-precision surgeries (neurosurgery, spinal, etc.), remote surgery, operational prep, radiology analysis, patient communication, and others. Specifically, researchers have identified three bodily elements that are known to benefit from three-dimensional representation: the brain, the pelvis, and fetal development. These elements are not the exclusive beneficiaries, but merely the most commonly identified.

As one specific usage example, a common challenge in radiology is that radiologists view and analyze Magnetic Resonance Imaging (MRI) data in their captured format of image slices, whereas surgeons think and operate in 3D, ultimately needing to create an accurate 3D model of the data in their mind in order to execute a procedure. Accurately and efficiently representing this data in both formats simultaneously should reduce overhead and improve communication, and ultimately results.

In another example, modern neurosurgery involves Neuronavigation, which is defined as "image-guided neurosurgery". Current Neuronavigation systems typically present the surgeon with several orthographic 2D projections of the patient and the position of the instruments. Some also include 3D-on-2D representations, but ultimately it is left to the surgeon to interpret the visuals to recreate a 3D model of the current status in their minds. Here again a natural 3D representation would reduce the cognitive effort required and should thus reduce time and surgeon fatigue and improve performance.

Agus et. al [55] have demonstrated a horizontal-only parallax light field display with volume rendering capability which showed some evidence of improved performance, where full parallax would be expected to provide a more flexible arrangement where viewers can collaboratively view displays from a variety of directions.

6.3 Air Traffic Control

Managing air traffic is an inherently multi-dimensional problem, with significant spatial and temporal demands, along with constant tracking factors such as speed, fuel level, mass, passenger load, weather, etc. The training and selection process for this task is extensive and involves very high failure rates, while the ongoing stress of the job leads to very high attrition rates. Qualifying for the job requires specific personality traits and a highly developed sense of spatial awareness and reasoning - the primary source of the high failure rates.

Many of the described challenges can be traced back to cognitive loading. Controllers are expected to take in and track a great deal of disparate data, and must build a 3D spatial and temporal model of the state of the airspace in their minds in order to make decisions. While it is not a scientific reference, the directors of the film Pushing Tin (a movie about Air Traffic Controllers), explicitly depict this translation of the ATC's mental state into a 3D map as the most effective way to communicate the controller's experience to the audience. Perhaps more scientifically, some experimental results have suggested that stereoscopic-only 3D displays can improve some ATC task performance [45], leading to a strong hope that full light field displays would offer further improvement possibilities.

The technologies currently used in ATC are surprisingly modest and largely based on systems that are 20+ years old, derived from traditional flat swept 2D RADAR. Some installations even continue to use swapped placards to track the order of aircraft landings, which is a practice from the 1960s. A system that can represent the spatial and temporal relationships between all aircraft in the airspace should significantly reduce this cognitive load and reduce the controller's workload, leading to better decision making.

6.4 Enhanced Detection, Navigation and Ranging (RADAR, SONAR, etc.)

As noted in the discussion of ATC, RADAR systems have traditionally been visualized directly from the nature of the underlying technology - that is, a sweeping line that shows reflected contacts when they appear. Modern radar systems are able to detect much more specific 3D information about contacts (altitude, even shape in many cases), particularly when fused with other data sources. But many modern visualization systems do not yet leverage this information to its full potential. Weather radar systems already exist with 3D representations, but these too are not as commonly deployed as they could be, and this may be due to limitations of representing the information on a 2D display.

Today's SONAR visualization systems have a very different operating principle and representation, but they too are fundamentally tied to the underlying technology. In this case, the data is inherently 3D, and thus very amenable to being represented on a holographic display. For example, navigating complex underwater terrain using bathymetric sonar data is a task that should be inherently easier and more accurate when viewed on a natural 3D display. Visualizing enemy assets and torpedoes within the 3D underwater space should also be inherently faster and easier when depicted holographically.

6.5 Training and Simulation

"Train Like You Fight" is a common refrain in defence applications. As part of that mantra, one of the objectives is to make the training experience as realistic as possible. Unfortunately, 2D displays that attempt to depict real-world 3D situations inevitably fail in this goal, due to a lack of fidelity. Whereas natural 3D holographic displays can greatly improve the fidelity of the training experience, leaving the user believing that what they are experiencing is real. This is true of immersive trainers, as well as part-task trainers, and is particularly important in cases where multiple users are involved. Technologies such as Virtual Reality (VR) can improve the immersive experience, but also restrict the user to isolation from other participants. Additionally, these technologies induce a number of unpleasant side effects ("simulator sickness"), which is detrimental to training.

Most armed forces have a stated desire for a "fully reconfigurable training environment". While this can mean many things in different contexts, what's ultimately desired here is the equivalent of the Holodeck from the Star Trek TV and movie franchise [56]. This capability would allow any and all training to be conducted in the same location, and quickly modified to meet the needs of the individual trainers and/or trainees. The long-term goal of holographic display technologies is to make this kind of training environment possible, with the one critical exception that objects in the training environment are made of light and thus cannot be interacted with physically - though this can be mitigated through the use of haptics and other technologies.

6.6 Computer-Aided Design (CAD) and Analysis

CAD has long used 3D-on-2D representations of objects to improve the design process. While these technologies have always been hampered by the limitations of 2D displays, they remain a critical tool for visualizing and analyzing designs of real-world objects. However, the benefits of a truly 3D holographic representation in this area are obvious – the equivalent of a run-time 3D printer for which the designer can perpetually make changes to the design and see how they impact the relationships with other design elements.

Companies such as Boeing have famously developed their own CAD tools, specifically because of unique 3D visualization requirements that weren't met with the existing tools of the day [57], [58]. Many of these larger companies (manufacturers of aircraft, vehicles, etc.) have even used actual 3D models made from clay or other materials to communicate their artistic and technical ideas to colleagues, superiors and customers. The ability to depict these 3D designs in a natural way to multiple viewers is already shown to be highly desirable. Products by companies like Dassault (makers of SolidWorks, CATIA and other tools) and AutoDesk can derive immediate and obvious benefits from holographic display technology.

Beyond the design process, 3D visualization has also been a critical element of tools used to analyze dynamic systems, such as engine designs, airflow, etc. Products such as SIMULIA (also by Dassault) can benefit from 3D holographic representations as a more natural way to depict the results of their simulations. Further, fault analysis tools for analyzing data captured from existing equipment - part of the growing "Digital Twin" movement - may improve the ability to identify and resolve problems in live equipment faster and more accurately.

Beyond the selected use cases, there are several other known defence applications for holographic displays, such as virtual windows, targeting systems, remote control of semi-autonomous drones, and others.

In all of these cases, there is always a tension between adoption of a new technology that may deliver improvements, vs the risks of disruption generally and the impact on training and phasing in any changes. While these issues are beyond the scope of this paper, they are recognized as an important element of any adoption strategy, and must be carefully considered. Similarly, many of these application areas require not only adjustments to the visualization systems being used, but also to how the underlying data is processed and organized. Again, this is beyond the scope of the paper, but an important topic to assess while considering new visualization technologies.

7.0 SUMMARY AND CONCLUSION

New technologies that provide improved visual computer interfaces have significant potential for improving the usefulness of digital technology. High fidelity holographic 3D displays will soon arrive, providing an enhanced visual interface experience free of many of the issues surrounding HMDs. These displays will provide focus cues which induce a natural accommodation-convergence response in the eyes with full motion parallax. Existing holographic technology does not yet provide the desired experience, but with some advances beyond current technological limits, these displays will become highly usable in a wide variety of settings. Future displays will be based on greater pixel densities, more flexible optical systems and high-throughput rendering systems that can drive the massive bandwidths that will be required for holographic video.

Many existing studies strongly suggest that future holographic displays will provide users with enhanced capabilities for learning, planning, analysis and decision making. This is because a light field gives viewers the perceptual cues that they are used to having when viewing the real-world. While obviously this promises to give improved visual realism, existing studies seem to suggest that it also results in decreased cognitive loading when viewing data and information on the display. Once such displays become available, more complete studies will be required in order to further quantify the improvement such displays may provide and also how various factors (e.g. the way data is mapped to visual output) may influence this improvement. We have described a number of promising use cases where holographic displays promise to provide significant advantages in terms of improving user performance in data analysis tasks and we believe these areas should provide a starting point for further studies that verify the improved experience holographic displays promise to offer, ultimately providing the defence community with a tool they may leverage for overall effectiveness in a variety of areas.

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