The First 20 Years of Holographic Video – and the Next 20

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Abstract. The late Professor Stephen Benton, co-inventor of the world's first holographic video system, sometimes quipped that we were "only 3 Nobel Prizes away" from a practical product. This presentation describes the baby steps, technical breakthroughs, and most recent (perhaps even prize-worthy) developments in this exciting new medium. Topics covered include: Why is it so difficult? (Or, how to handle a terabyte per second.) What technologies enabled the invention of holographic video, and how far have they progressed in the 20 years since? What technological advances will be part of holographic video 20 years hence? How might visual entertainment and communication adapt to a (holographic) volume paradigm? (Or, how we will learn to "box" a shot – rather than "frame" it?) Light-modulation technologies, computational architectures, holographic algorithms, photonic processing, and spatial scene representations – all of these cutting-edge technologies play important roles. Included will be a glimpse of the new full-parallax, full-color holographic display prototype, developed by Zebra Imaging during the past 5 years with support from DARPA.

Keywords. Holographic displays, holographic video, three-dimensional displays, hogel, hogel-based imaging, holographic computation, holography, lightfields, holographic bandwidth compression, holographic encoding, holographic communications, holographic capture, crowd-based capture.

Introduction

Since its inception more than 20 years ago, the electronic display of dynamic holographic images continues to move from the realm of science fiction into the realm of practicality. Numerous challenges have been identified and addressed through innovative application of rapidly advancing component technologies, e.g., light modulation techniques, information encoding, and the inexorable increase in computational power from increasingly ubiquitous integrated circuit chips. Today more than ever before, real-time holographic displays promise to enhance numerous applications involving the creation, manipulation and enjoyment of information, including entertainment, education, training, telepresence, medical imaging, interactive design, scientific visualization and military applications.

The first electronic, interactive three-dimensional (3D) holographic imaging system was achieved in 1990 at the MIT Media Laboratory at the Massachusetts Institute of Technology[1]. Researchers were at last able to create real-time electro-holographic displays ("holovideo") by confronting the two basic requirements of electronic holography: computational speed, and high-bandwidth modulation of visible light[1-6]. The first electro-holographic displays created images occupying a small image volume (50 cc), requiring several minutes of computation for each update[6]. Later approaches, employing innovations such as holographic bandwidth compression and faster digital hardware, enabled computation at interactive rates and the continued increase in the size and complexity of displayed holovideo images. Figure 1 shows typical images displayed on the early MIT 6-MB full-color holovideo system. A later larger holovideo system created an image volume that was as large as a human hand (about 1,000 cc or one liter)[3].

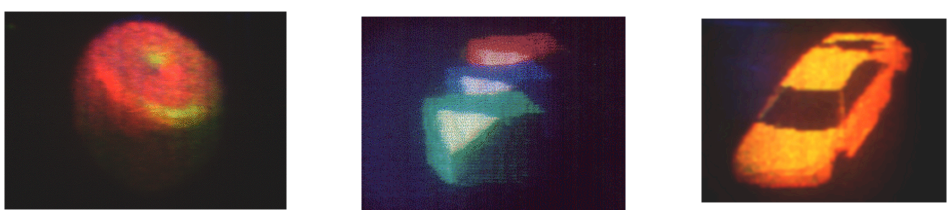

Figure 1: First holographic display systems: photographs of 3D holographic images, shown approximately to scale: (left) red apple with multi-color specular highlights[1]; (middle) red, blue, and green cut cubes[2]; (right) yellow car body[3].

By 1990, holographic displays had become a laboratory reality. However, given the challenges, why endeavor to create dynamic electronic holographic display products? Instead, why not employ some other 3D imaging techniques, such as stereoscopic, or auto-viewable stereoscopic (discrete-parallax or "multi-view"), or volumetric displays[7-10]? The answer is that only holographic displays can achieve the full realism and true-3D images enjoyed by our visual system when perceiving the real world. Only a properly designed and constructed electronic holographic display can create a truly 3D image with all of the depth cues (motion parallax, ocular accommodation, occlusion, etc.) and resolution sufficient to provide extreme realism[5,7-14]. In contrast, an image created by a stereoscopic display[7-8] creates the illusion of 3D by providing binocular disparity; however, the human visual system still sees a flat plane of pixels, resulting in conflicts among depth cues that can lead to eye fatigue, headaches and nausea. Volumetric displays can create dynamic 3D images, but fail to provide some important visual depth cues (e.g., shading, texture gradients) and cannot provide the powerful depth cue of overlap (occlusion). Discrete parallax displays (such as lenticular or parallax-barrier displays) create 3D images with the addition of a limited amount of the depth cue of motion parallax, but fall short of producing a truly 3D image[7-10].

Basics of Electronic Holographic Display Systems

To understand electronic holographic imaging, first consider how traditional optical holography is used to produce 3D images. It begins by using coherent light to record an interference pattern with sub-micron features[11]. Subsequently, the recorded holographic fringe pattern (called simply a "fringe") modulates illumination light, which propagates ("diffracts") to form a 3D image. In general, a region of a fringe contains a variety of spatial frequency components – recorded information that corresponds to both the intensity and direction of light (needed to create an image). The extremely high spatial frequency content gives a hologram an enormous information content (i.e., space-bandwidth product): in a typical full-parallax hologram (i.e., light images vertically as well as horizontally), a 60-cm-diagonal traditional hologram has a of over 10^{12} samples – the equivalent of a terabyte!

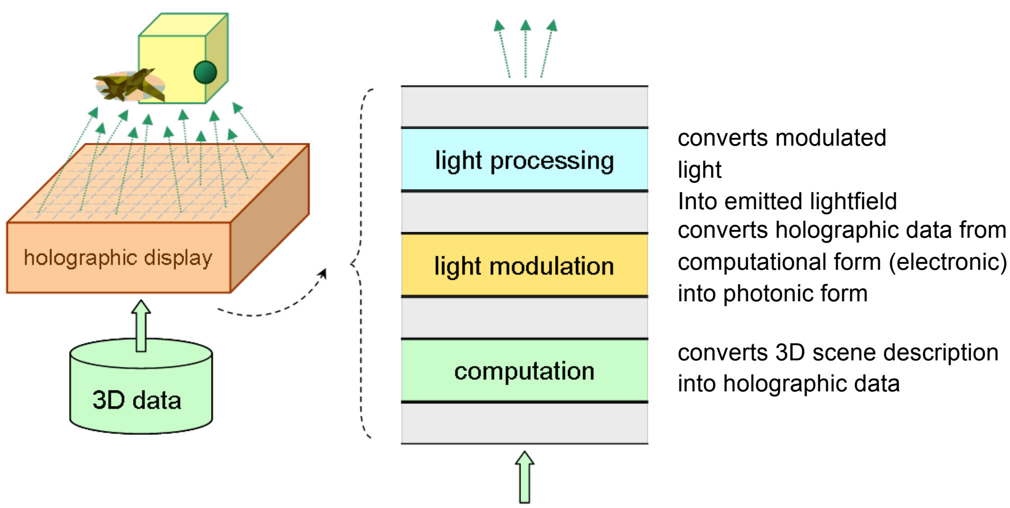

Figure 2: Basic architecture of a holographic display.

An electro-holographic display (or simply "holographic display") generates a 3D holographic image from a 3D description of a scene. This process involves many steps, grouped into two main processes: computational, in which the 3D scene description is converted into holographic information, and photonic, in which light is modulated by the holographic data and then processed optically to produce an image. (See Figure 2.) Holographic displays can follow a wide range of architectures; however, they tend to have the basic architecture depicted above. In the "computation" block, the holographic information is computed from the desired three-dimensional scene description. In the next two blocks – photonic processing – a three-dimensional image is formed when light is controlled using the application of holographic data (the "light modulation" block) and some amount of optical processing (the "light processing" block).

The difficulties in holographic computation and photonic modulation result from the enormous amount of information (space-bandwidth product or simply "bandwidth") represented by an optical wavefront or lightfield recorded in traditional optical holography. Consider that, whereas a two-dimensional (2D) image is treated as a pixel array with a sample spacing of approximately 100 microns as is common in a 2D display, some holographic displays compute holographic data with a sample spacing of 0.5 microns or smaller. Electro-holographic displays can have internal bandwidths that are a factor of about 40,000 times more than in 2D displays. Horizontal-parallax-only (HPO) imaging eliminates vertical parallax resulting in a bandwidth savings of over 100 times[1]. However, HPO images are astigmatic, and are therefore inherently difficult to view for large image volume depths.

Holographic Computation

The computational process in electro-holography converts a 3D description of an object or scene into holographic information – necessarily containing a representation of the lightfield needed to image a 3D scene. (A lightfield is here defined as information describing the amount of light that must propagate from each location in the hologram and in a wide range of directions.) Holographic computation comprises two stages: a computer graphics rendering-like stage that results in the lightfield required to image a specific scene, and a holographic generation stage which results in holographic data that has encoded in it both the lightfield information and the physics of optical propagation (diffraction) through the photonic portion of the holographic display. The computer graphics stage typically involves spatially transforming polygons (or other primitives), lighting, occlusion processing, shading, and (in the case of live video) a stream of multi-view video. In some applications, this stage may be trivial; for example, range data (from light-based radar or *lidar*) may already exist as a point cloud.

Holographic computation approaches differ by the degree to which they imitate the physics of traditional optical holography – ranging from interference-based to the more refined diffraction-specific approach, and onward to approaches that comprise just enough physical simulation. Typically, close simulation of physics is costly but results in a high-fidelity image. Thus, one of the crucial decisions in designing a holographic display is the careful trade-off between high fidelity and low cost. In some cases, moving away from strict simulation of traditional optical holography can improve image quality; for example, unwanted intermodulation artifacts can be avoided by taking an approach based more on the computational imaging than on traditional optical holography[1].

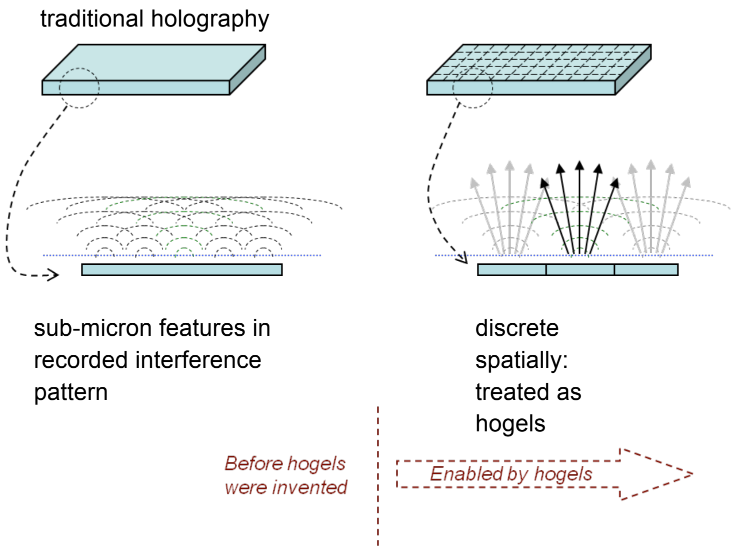

Figure 3: Invention of the hogel and its impact on information density[5].

In digital holography, the holographic plane or surface can be treated as spatially and spectrally discretized, i.e., in space and by k-vector (directional vector); see Figure 3. It can be treated as an array of holographic elements called *hogels*[5]. Hogel-based imaging expresses holographic information as a four-dimensional array of samples, with two spatial dimensions and two k-vector (directional) dimensions, thus fully representing the lightfield recorded in a traditional hologram (within the information theoretical laws of sampling) but in a much more compact form. (Note: the arrows shown in Figure 3 represent sampled directional information; light emitted from a hogel typically is not a set of discrete wavefronts, but is instead a set of overlapping wavefronts, when properly constructed.) Hogel-based imaging dramatically reduces holographic bandwidth and computational complexity; therefore, it greatly increases computational efficiency and often decreases the cost of photonically processing the holographic information[3-5].

Before the invention of the hogel and its associated spatial-spectral discretization, the conventional approach to computing holographic data was to simulate optical interference, the physical process used to record optical holograms[11]. This approach produces an image with resolution that is too fine to be fully utilized by the human visual system. And, as stated above, its lack of any light processing leaves the bandwidth large and the cost high on both computation and light modulation. To compute an interference pattern following basic laws of optical propagation, complex wavefronts from object elements are summed with a reference wavefront[1], resulting in billions of computational steps for small simple holographic images. Early researchers used supercomputers[1]; later, graphics hardware was employed[2].

The diffraction-specific approach, based on the invention of the hogel, breaks from the traditional simulation of optical holographic interference by working backwards from the 3D image[3-5]. The digital hologram is treated as a spatial-spectral array of hogel vectors (so called because they represent sampling across the directional k-vector) – similar to lightfield representations. The hogel-based diffraction-specific approach increases overall computation speed and achieves bandwidth compression by reducing complexity in both dimensions of the holographic fringe data. For full-parallax displays, good performance is achieved for a compression ratio (the ratio between the size of the holographic fringe data and the hogel-vector array) of $(16:1)^2 = 256:1$ or $(32:1)^2 = 1024:1$. A reduction in bandwidth is accompanied by a loss in image sharpness – an added blur that can be matched to the acuity of the human visual system simply by choosing an appropriate bandwidth compression ratio and sampling parameters. In the case of HPO displays, a compression ratio of 16:1 or 32:1, good images are still achieved, with acceptable image degradation[3]. Diffraction-specific fringe computation is fast enough for interactive holographic displays and video-rate updates; however, the additional strength of hogel-based computation is that it also enables the easy application of specialized hardware, which can be utilized for these simple and regular calculations, resulting in tremendous speed improvements[3-5,11,15,16].

Photonic Subsystem: Light Modulation & Light Processing

Traditional optical holography creates an image without using any optical processing after light modulation, i.e., it relies only on optical propagation (diffraction) and the response of the human visual system. Therefore, the interference-based approach – highly analogous to traditional holographic imaging – is a "naked" approach, one that uses the holographic data in brute-force mode, which places a maximum burden on the computation and light modulation steps. In traditional hardcopy optical holography, the modulation is performed by high-resolution light-recording film, which is relatively affordable compared to 10^{12} light-modulation elements required for an electronic equivalent[11-13].

In a typical holographic display, computation is followed by the photonic subsystem, in which light is modulated with the holographic data and processed to form the desired optical wavefront or lightfield. Information about the desired 3D scene passes from electronic/computational bits to photons by modulating light with computed holographic data, generally using a spatial light modulator (SLM) or some other light-modulation technology[1,6,11-13,17-24]. Given the enormous sample count, successful approaches to holographic light modulation use one or more of the following techniques:

1. parallelism, i.e., gang many modulators together
2. exploiting the limited time-response of the human visual system
3. use of a re-writable material to give the modulators a higher effective space-bandwidth product.

As described below, further successes can be obtained using a higher degree of encoding (e.g., fringelets, described below) to make the most of the space-bandwidth product of the available light modulator, linked with subsequent photonic processing (e.g., fringelet decoding).

Many types of SLMs can be used to convert holographic data from the computational domain to the photonic domain. Electro-optical SLMs based on liquid crystal (LC) technologies are commonly used for 2D imaging (televisions, computer monitors, office projectors, and mobile devices such as cellular phones and e-book readers)[12,17-24]. SLMs using liquid crystal on silicon (LCoS) can be extremely compact[20-22]. Other approaches include LED (light-emitting diode) arrays such as organic LED (OLED) arrays from producers such as eMagin or Samsung; micro-electromechanical (MEMS) such as micromirrors (e.g., from Texas Instruments, Inc.); microscanners (e.g., from MicroVision, Inc.); interferometric micro-modulators (e.g., Mirasol display technology from Qualcomm, Inc.,), and pico-projectors (Light Blue Optics).

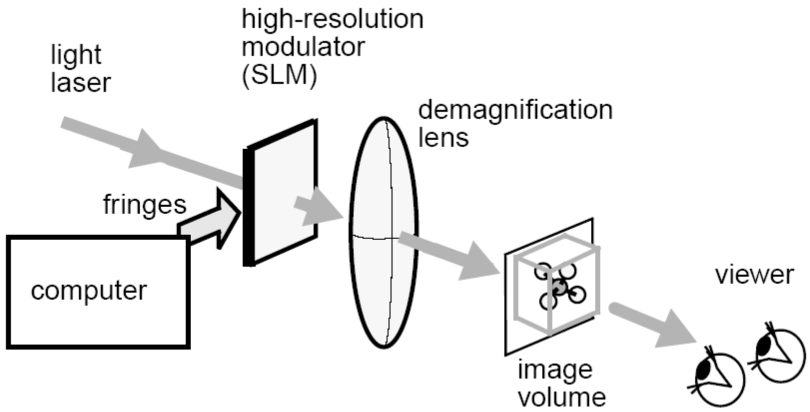

Figure 4: Holographic light modulation using a typical high-resolution modulator (SLM).

The light-processing portion of a holographic display system typically addresses the specifics of the light-modulation portion, including the many common short-comings. For example, the limited pixel count of typical SLMs is often overcome by using the light-processing subsystem to tile together many modulators. Another important example is demagnification: SLM modulation elements are usually too big – typically 5 to 500 microns center-to-center. Demagnification can be employed to reduce the effective sample size – as shown schematically in Figure 4 – with the necessary but unattractive effect of proportionally reducing the lateral dimensions of the holographic image volume. Stated another way, consider that the space-bandwidth product of a traditional optical hologram that produces a true-3D image is at least $\sim 10^5$ samples per square centimeter of display surface – and as high as $\sim 10^{10}$ samples/cm^2! For an electronic modulation system to match this capability, there is simply nowhere to put the modulators inside a display, unless the modulator elements are very, very small.

Time-Multiplexed Modulation: Another example of photonic processing involves the rapid time-multiplexing of very fast SLMs. The earliest example was a scanned acousto-optic modulator (AOM). By scanning the image of modulated light with a rapidly moving mirror, a much larger apparent fringe can be modulated. The latency of the human visual system is typically 20 ms, and the eye time-integrates to see the entire fringe displayed during this time interval. This technique was invented and exploited by researchers at the MIT Media Laboratory to produce the world's first real-time 3D holographic display in 1989. The light-processing portion of these early displays comprised two lenses for demagnification as well as both horizontal and vertical scanning systems, which angularly multiplex the image of the modulated light. After the last stage of photonic processing, the lightfield formed an astigmatic 3D image possessing horizontal parallax[1,6]. More recently, researchers have used an AOM device with multiple ultrasonic transducers, which are fed a complex computed pattern and launch surface acoustic waves (SAWs) or channeled acoustic waves across the device aperture[11,13]. Novel light-processing may eliminate the need for time multiplexing and consequently scanning mirrors.

Diffraction-specific, hogel-based fringe computation leverages the light-processing portion of the display system (Figure 2), and thus opens up a new frontier in holographic displays, in which novel light-processing subsystems can be designed and exploited to greatly simplify holographic computation and light-modulation. The resulting potential to reduce cost and increase performance has only begun to be explored. For example, fringelet bandwidth compression further subsamples in the spatial domain[4-5]. Each hogel is encoded as a spatially smaller "fringelet." Using a simple sample-replication decoding scheme during the earliest days of holographic displays (c. 1993), fringelets provided some of the fastest methods of generating a diffraction-specific fringe pattern, allowing complex images to be generated in under one second for 6-MB fringes[4]. Furthermore, a "fringelet display" can – without increased electronic bandwidth – photonically decode fringelets to produce an image volume that is greater in proportion to the compression ratio[5]. In the fringelet approach, the photonic subsystem of the display is incorporated into the holographic computation process, i.e., fringelets are generated to match and complement the particular optical behavior of the photonic decoding subsystem (the light processing block shown in Figure 2).

Holographic Displays from Zebra Imaging

More recently, work at Zebra Imaging, Inc. (Austin, Texas), has resulted in the most advanced holographic displays to date[25,26]. Led by author, the conception and development of this holographic display technology was based on some of the earliest work in holographic video[1-5]. By leveraging novel light-processing architectures and incorporating them into our proprietary holographic computation algorithms, we have achieved the highest yet level of performance, while dramatically increasing the practicality of holographic display systems, for both commercial and military applications[25,26]. (See Figure 5).

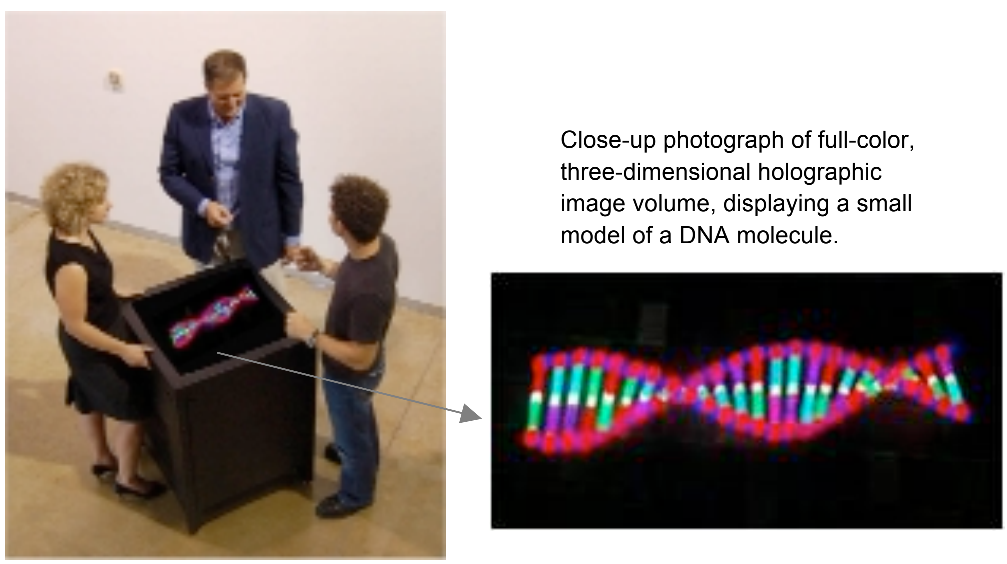

Figure 5: Zebra Imaging prototype holographic display (left), with image overlaid[25,26].

Starting in 2005, and funded in part by generous support from Defense Advanced Research Projects Agency (DARPA)[26], Zebra Imaging has developed a flexible holographic display platform[25], with all of the advantages inherent in electronic holography – and then some:

- Natural 3D (no eyewear), continuous viewing
- Full-color, bright, true-3D images

- Fully interactive, as well as live video content
- Precise spatial registration, independent of the location of multiple simultaneous viewers
- Text-legible quality: resolution > 10 million, for 60-cm diagonal image volume
- Team viewing – wide viewing range enhances collaboration.

The objective of the 5-year DARPA program was "to develop a large holographic display to facilitate rapid and clear communication of intelligence for team-based mission planning and rehearsal, visualization and interpretation of real-time data, and training", and the results exceeded expectations[26].

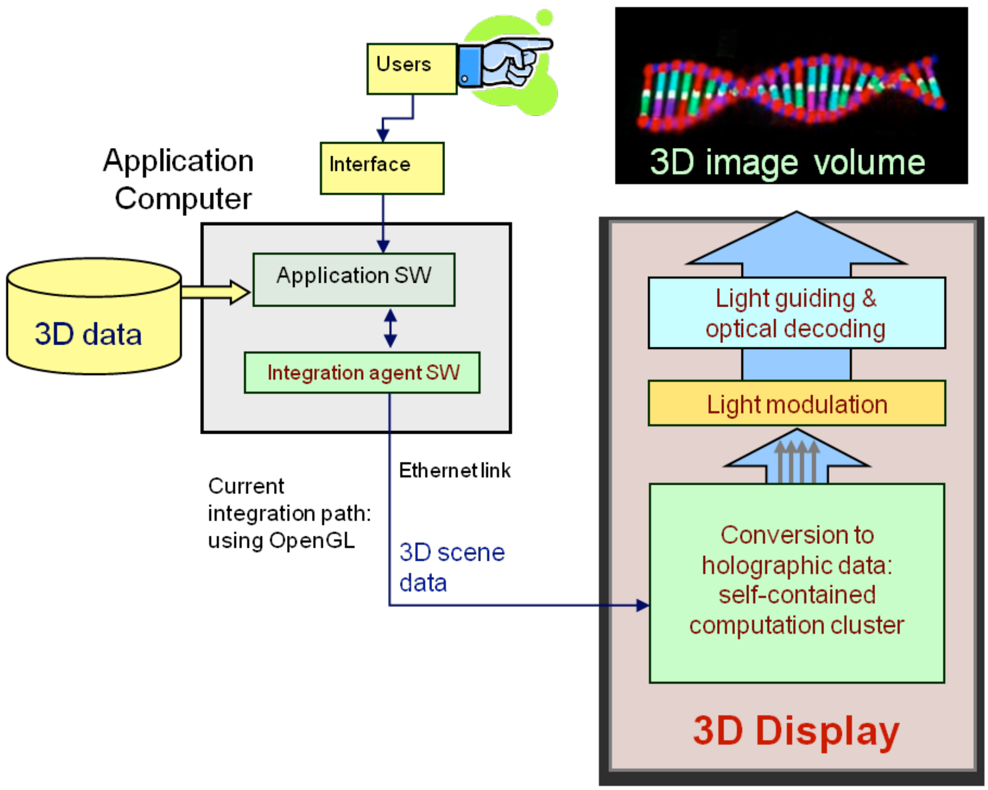

Figure 6: Holographic display prototype from Zebra Imaging – Functional description

Figure 6, above, illustrates the basics of the holographic display prototype shown in Figure 5. The display comprises the three subsystems that are typical in any holographic display. Three-dimensional scene data (which enters the display via an Ethernet connection) is converted by the computation subsystem into holographic data, which is converted into photons by the light-modulation subsystem. The modulated light passes through the light-processing subsystem and emerges from the display as a lightfield to produce the spatial true-3D image, which occupies a volume that is approximately 30 cm axially and the lateral dimensions of the display window (45 cm for the display in Figure 5).

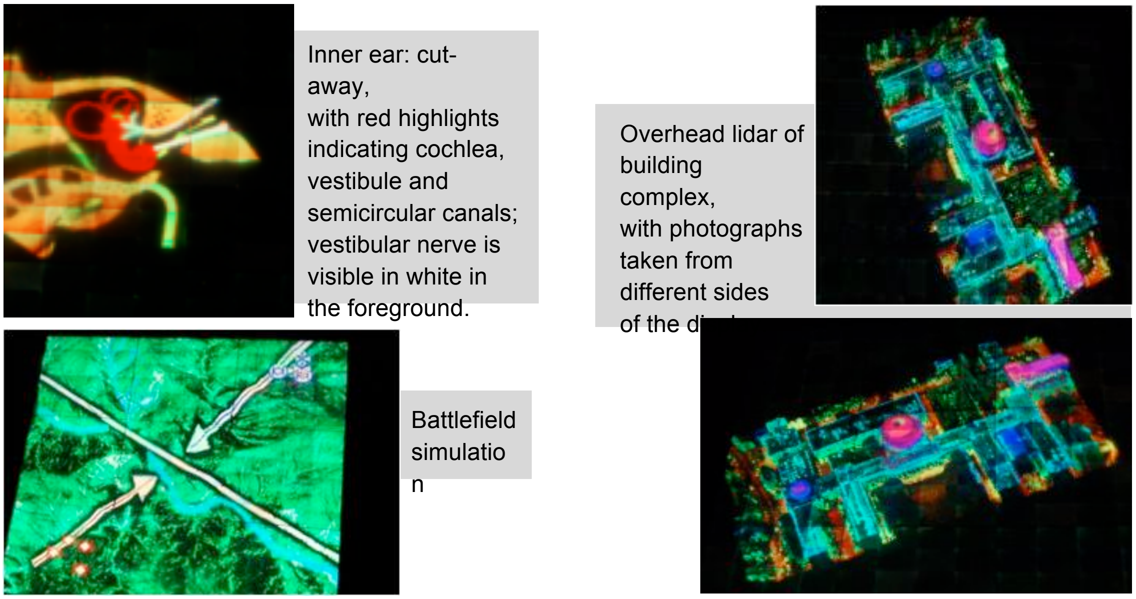

Figure 7: Photographs of holographic images generated by Zebra Imaging prototype display.

The holographic image, produced in real time at interactive rates, is a dynamic three-dimensional body of photons, and possesses all of the depth cues of real-world objects, making comprehension rapid and accurate. Interactivity is directed by the front-end software application (Figure 6), and has already been demonstrated using a wide range of interaction modalities, including 3D tracked wands and gloves, multi-touch, and video-game-like pointers.

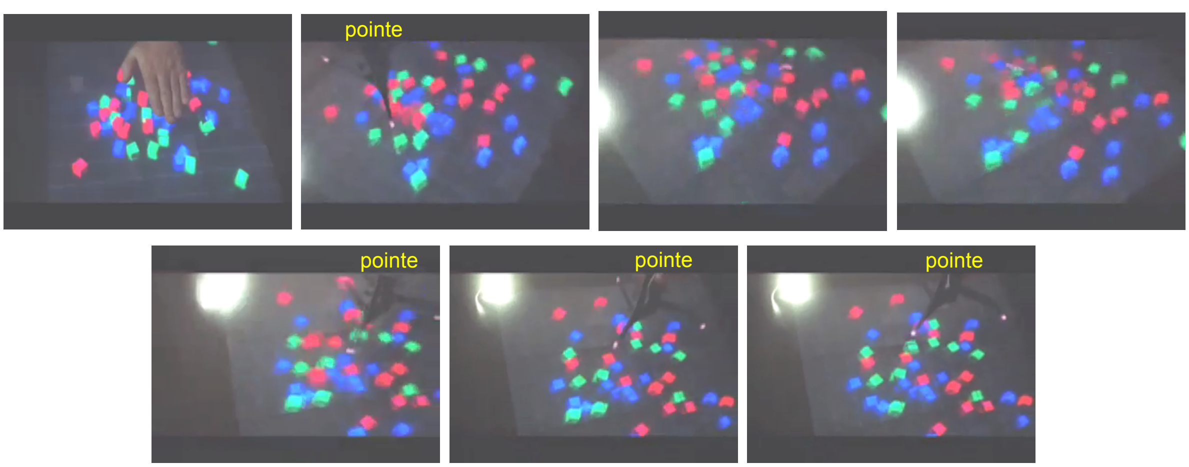

Figure 8: Interactivity – Sequence of photos taken during an interactive demonstration.

Figure 8 shows a number of colored cubes being moved by the user, in this case employing a spatial pointer wand. Update rates for full-color imagery with moderate complexity (as shown above) is better than 3 updates per second, with a response time of less than 0.3 seconds after each user event. Pre-computed animations can be played on the display at speeds of 10 Hz and greater[25,26].

Interpretation and interaction are intuitive and natural; those who see images on the prototype displays are able to quickly understand and use the 3D interaction devices to manipulate images. (See illustration, above, which shows a 3D pointer being used to manipulate colored cubes in the image volume.) Current form factor is either horizontal window (like the top of a table), vertical (like a desktop computer monitor), or any intermediate tilt angle. The current prototype represents a robust, flexible platform for these continued developments, and will evolve into a range of capabilities, from its current workgroup platform to smaller and more mobile platforms (workstation, then portable, and then mobile). Also possible will be larger systems – wall-sized and even-arena sized.

Zebra Imaging is currently transitioning the holographic (UPSD) display prototype systems to Department of Defense customers[26]. With the support of DARPA, we are "initially transitioning the UPSD technology to an Air Force research center and two Army research centers to apply the technology to critical applications where the 3D holographic display will provide a unique benefit"[26]. The first involves the U. S. Air Force, in which Zebra Imaging "will integrate its interactive 3D holographic display system … with a United States Air Force Warfighter mission application related to air, space or cyberspace warfare. The 24-month Phase II effort will demonstrate the utility of dynamic, holographic display and 3D user interaction specific to the Warfighter's environment. Phase II will also further develop, optimize, and integrate 3D holographic visualization with Air Force Warfighting missions, data flow, tactics and support structure" [27].

Our long-range target is to create holographic display products with image quality and sizes that match and exceed our current print hologram products[28], and at price-points that allow wide-spread deployment throughout the community, providing high-fidelity visualization for entertainment applications, as well as for medical, geoseismic, control centers, simulation and training. The range of imagery types will be extended to include multi-stream live feeds; already, under DARPA's guidance, these prototypes have been demonstrated at several conferences, including demos of full-motion holographic video as early as 2008. At present, image depth and resolution is limited only by cost, and will improve dramatically as new generations of computation and light-modulation innovations continue to progress at historically extreme rates. By leveraging "tera-flops" and "mega-pixels" as their unit costs drop below a dollar each, our holographic display platform can be extended to produce imagery that is as sharp and deep as Zebra's current print holograms[28].

Future of Holographic Displays for Motion Pictures and Broadcast

As of the year 2011, there are no off-the-shelf holographic displays. This is likely to change very soon due to a steady stream of innovation, as well as two important trends: the seemingly relentless reduction in the cost of complex computation (sometimes referred to as "Moore's Law"); and the ever-decreasing cost of light modulation. Although photonic modulation and light-processing have borrowed from existing technologies (e.g., transmissive LCDs, AOMs), new technologies will fuel the development of larger, more practical holographic displays. This is evident in the explosion in popular use of electronic displays, including mobile phones, e-book readers, digital signage and even wearable displays.

Looking ahead 20 years, in the entertainment space, user demand is crucial to the development of practical holographic display products. As other types of 3D display technologies (e.g., auto-viewable stereoscopic displays) acquaint users with some of the advantages of spatial imaging, these users will grow hungry for holographic displays, technology that can produce truly 3D images that look as good as – or better than – actual 3D objects and scenes. And demand may be driven not so much by fidelity (as in high-definition television) but perhaps more by the extreme "clarity" achievable in holographic imaging – the emotion, intelligence, response that are essential to cinema, and the broadcast of sports and news.

Interactivity: Holographic displays offer extremely rich interactivity. The world of broadcast and entertainment typically combine both of the extreme modes of interaction: the "out the window" mode (or "far away" mode), and the more intimate "arm's reach" mode. Viewers – especially of sporting events – might want to blend traditional birds-eye views with specific in-the-action viewing. Holographic displays can provide both – using simple interaction or more advanced spatial gestural interactivity. Holographic imagery can be naturally explored – like looking at real-world objects. Content will be flexible and explorable: instead of just passively watching shot after shot, a viewer might choose to zoom in and/or pause, to explore in detail, both spatially and temporally. Traditional cinema may continue to think of "framing" a shot – an inherently two-dimensional concept in which the director/cinematographer selects a subset of the spatial scene – making interactivity less appropriate. However, in a future with holographic video imagery, content creators and capture operators may think in terms of a "box" or "avenue" – one that supports exploration by the viewer of holographic video imagery. Sports, education and social media are example in which the user might benefit from exploring holographic content in this manner. For example, in most sports events, fans might select a view position, such as just behind the home team's bench, or *on* the playing field, or tracking behind whoever has the ball. Imagine watching a boxing or volleyball match holographically, and putting yourself just behind or next to one of the contestants.

Communication: Where will holographic content come from, and how will it be communicated to holographic displays? These questions are not yet answered. However, an important part of the solution will be object-based content representation. Object-based encoding can make efficient use of bandwidth, but also allow for a wide range of capture and display systems. For example, MPEG4 is a step in the right direction, allowing for encoding of objects in a scene (instead of just arrays of pixels), and empowering displays to decode at native resolution and capabilities. YouTube represents another inspirational example: it adapts to different size displays, and different bandwidths of different communications infrastructure. The movement away from pixel-centric encoding to a more scene-centric encoding will accelerate the adoption of holographic video.

Capture: Holographic capture systems will emerge – based heavily on the highly compute-intensive techniques of machine vision and computational imaging. For example, a modern stadium is a capture device – for television, and more recently for YouTube and social media – with facilities increasing designed for electronic input, many of them embedded (including sky cameras, lights for crisp TV images, dynamic backdrops to spice of the scenery). Looking ahead, in an arena or stadium in 2031, data streaming from embedded arrays of 2D cameras and spatial sensors (such as lidar) will be fused and processed to extract omniviewable spatial models of the action – in near real time. This extracted dynamic 3D model can be transmitted and/or broadcast to remote locations, where users can view the action holographically – but can also interactively direct perspective, choosing the best seat in the house as action and interest shifts.

Conclusion

The elements of holographic display are rapidly and often unpredictably changing and advancing, as are the technologies that will support holographic capture and communication. As a parting example, consider a holographic capture approach based on the capture devices carried by us every day at sports and red-carpet events: when fans hold up their smart phones and digital cameras, the action is being captured from many perspectives, simultaneously. Services, infrastructure and algorithms may soon exist to securely and cost-effectively share and fuse the captured video – from devices that are held or worn by users, and embedded into the surrounding – to extract spatial models, which are then available to be viewed holographically anywhere. This crowd-based capture (or "crowd-cap") approach has many fascinating and challenging implications in many realms: technology and business, as well as fashion, architecture, artistic expression, privacy, law and politics. Exciting, intriguing, and perhaps a bit scary – but the genie is already out of the bottle.

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