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Holography: The Next Disruptive Technology

by Tomoko Sano

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14. ABSTRACT

Camouflage has been used by the US Army for years for concealment and obscuring objects. Though effective, this is a relatively simple passive-defense tactic with limitations. Augmenting or manipulating reality to confuse and deceive the enemy would be the next innovative step forward. Is it possible in the future to create a deceptive holographic army or a holographic concealment in the battlefield? Using a 2-D screen and holograms for training purposes and for meeting face to face, as well as touchscreen haptic holographic displays, are already possible. The ability to project true holographic 3-D objects in air using femtosecond lasers that can be viewed from all 360° angles was just developed. What is the timeline and what are the technological gaps that must be solved before holographic innovations can revolutionize visual deception? And, how much shorter is the timeline for holography's use for training and communication applications without using special headsets or glasses? What are the promising methods and extent of capabilities of the various holographic projections being developed today? The objective of this deep dive is to search, review, and assess the current and rapidly changing technological advances in holography and how it could transform the Army's in-theater tactics as well as training and communication.

15. SUBJECT TERMS

holography, volumetric display, holographic display, 3-D projection, augmented reality, visual deception

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1. Introduction

The definition of holography is reflection of light projecting an object that is not physically there. The Hungarian–British physicist Dennis Gabor invented holography while trying to correct aberrations in the electron microscope, which led to his Nobel Prize award in Physics in 1971.[1] Since then a variety of methods of holography have been invented. Some are no more complicated than a modern version of "Pepper's Ghost", a 19th-century theatrical illusion in which an actor dressed as a ghost would be reflected off of a plate of glass. The audience would see the reflection in the glass but not the actor. Some consider these illusions "pseudo holography". Holography can be categorized into types: Stereoscopy, Autostereoscopy, Volumetric Display, and Holographic Projection.[1–3] Short descriptions follow.

Stereoscopic Displays: Stereoscopic 3-D displays show different images to each eye, where the image differences are based on a time sequence, wavelength, or polarization. Special glasses are required to perceive the image in 3-D.

Autostereoscopic Displays: Autostereoscopic displays still use 2 or multiple projections of images but do not require the use of glasses for the viewer to perceive the image in 3-D. The multiple-projection option allows for multiple viewers to perceive the images. However, the viewers' locations are limited. Once the viewers move out of position, the image is no longer 3-D or looks as intended. A method to alleviate the position limitation is to incorporate eye-tracking systems to adjust the images.

Volumetric Displays: Different groups have different interpretations of the term "volumetric display". Hence, the definition from Kovács and Balogh[3] will be used here. There are a variety of volumetric display types and methods. However, the underlying technique is the projection of the 2-D image onto a screen or onto a diffuse media to appear 3-D. Volumetric displays allow for full parallax, but some methods have issues with occlusion, or the blocking of one object by another, from different viewpoints.

Holographic Displays: Holographic displays use acousto-optic materials and spatial light modulators (SLMs) to project computer-generated holographic (CGH) images by a system using lasers and mirrors. The quality of the 3-D image is better than the other techniques and provides depth cues from all viewing points, but its applicability is limited due to processing of the large number of complex algorithms for the hologram.

Part I of this report will focus on materials and chemistries investigated for these displays, and in Part II the techniques of volumetric and holographic displays will be covered. More details of the other techniques can be found in Yang et al.[1]

2. Part I: Materials

The materials solutions for the holographic display technology are varied and dictated by the technology behind the holographic display. Some of the materials requirements and solutions for holographic display covered by Geng[4] and others are described in the following.

One method used in volumetric 3-D displays is to use a 2-photon upconversion to selectively excite and fluoresce voxels, or volumetric image elements, at desired locations. For the 2-photon upconversion process, a material that is able to exhibit 2-photon absorptions by 2 intersecting laser beams is required. One such material is zirconium tetrafluoride-barium fluoride-lanthanum fluoride-aluminum fluoride-sodium fluoride (ZrF_4-BaF_2-LaF_3-AlF_3-NaF, or ZBLAN), a fluorozirconate glass. Figure 1 shows the 2 infrared photons from wave lengths 11 and 12 exciting an ion, both of which fluoresce when transitioning to a lower energy level.

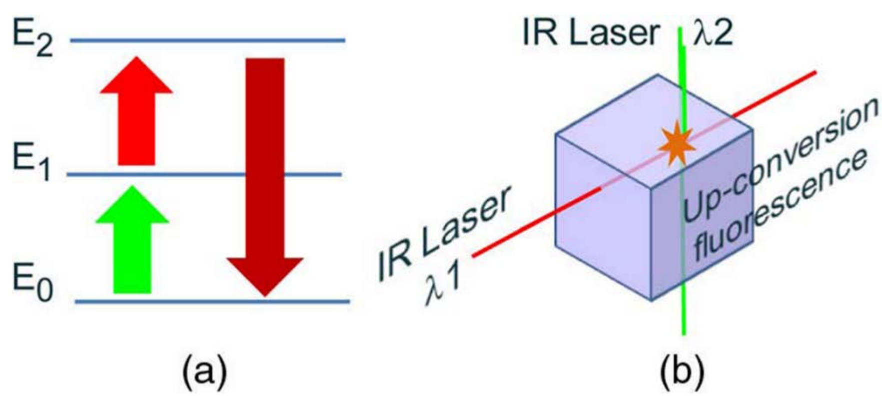

Fig. 1 Solid-state upconversion: (a) energy-level diagram of an activated ion and (b) 2 intersecting laser beams with different wavelengths are absorbed in ZBLAN (image reprinted with permission of Geng[4])

For static 3-D displays, one method is forming layers of liquid crystal (LC) or polymer-dispersed liquid crystal (PDLC) sheets that make up a 3-D volumetric screen. To display the images, the layers of LC sheets are switched on by applying a voltage. The correct 2-D image is displayed on the proper LC sheet location to create a 3-D volumetric image. The material solutions for these LC sheets require the capability of fast switching times of 0.1 ms (which is not commercially available), adequate brightness at 50-ms exposure times, and close to 100% light transmission for the displayed images to be transmitted through multiple LC sheets.

Another method for static 3-D displays is a 3-D glass cube embedded with optical fibers, as shown in Fig. 2. In this display, the germano-silicate optical fibers are used to control the 3-D voxel arrays, which are made from optical resin. The image signal is controlled by SLM, which also can have a variety of material solutions.

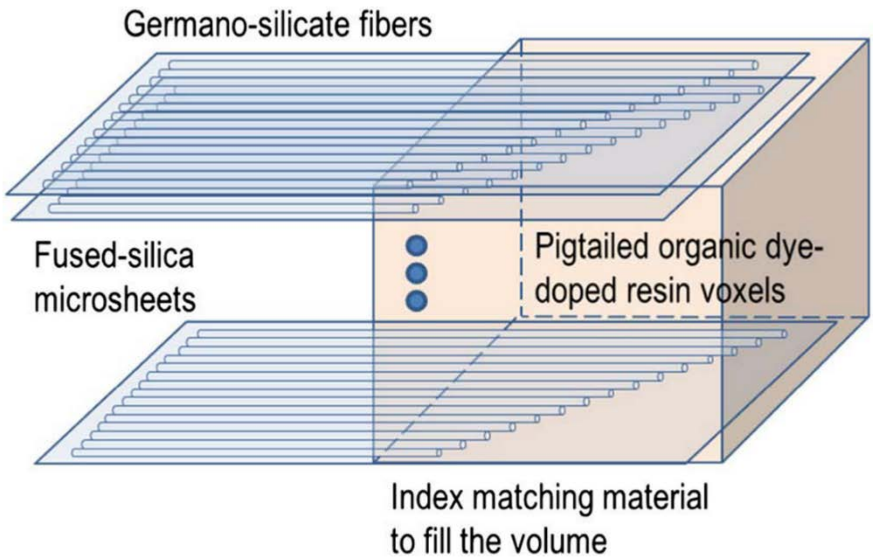

Fig. 2 Schematic of the optical-fiber-bundle-based static volumetric 3-D display (image reprinted with permission of Geng[4])

The SLM spatially varies the light intensity and/or the phase and is the key component in displaying CGH. There are a variety of SLM mechanisms, as shown in Table 1.

Table 1 Digital hologram SLM types and mechanisms[4]

SLM type	Modulation mechanism
Digital light processing	. . .
Liquid crystal on silicon	Electronically controlled
Ferroelectric liquid crystal on silicon	. . .
Acousto-optic modulator	Acoustically controlled
Optically addressed spatial light modulator	Optically controlled
Magneto-optical spatial light modulator	Magneto-optically controlled

Ferroelectric crystal on silicon substrate has been used for electrically addressed spatial light modulators, and optically addressed spatial light modulators use a chalcogenide glass family of materials such as amorphous arsenic trisulfide.[5] However, hydrogenated amorphous silicon film, bismuth silicon oxide, crystalline silicon, arsenic-selenium, phthalocyanine, and zinc oxide nanoparticle suspensions on an indium tin oxide-coated glass substrate have also been used for the photosensors.[6] For magneto-optic SLMs, layers of silicon nickel and amorphous terbium-iron thin films on silicon dioxide substrates[7] and bismuth-substituted yttrium-iron-garnet thin films have been used.[8]

A Massachusetts Institute of Technology (MIT) group developed a new SLM design with improvements in bandwidth, viewing angle, image quality, and color multiplexing. Their holographic scanner design, called the guided wave scanner (GWS), uses a proton-exchanged channel waveguide on a lithium niobate ($LiNbO^3$) substrate with a transducer at one end. The GWS consists of 2 sets of acoustic transducers to create surface acoustic waves that deflect light horizontally and vertically.[9] Other research groups[10,11] have investigated the application of lithium tantalite ($LiTaO^3$) or magnesium-oxide-doped $LiTaO_3$ thin film single crystals for the wave guide.

Other areas of materials development for holographic technology are for recording media applications. Beev et al.[10] details the variety and requirements of photosensitive materials and recording media, but the following is a short synopsis. For a material to be a candidate for a holographic recording media, several factors need to be considered: spatial resolution, diffraction efficiency, modulation transfer function, exposure sensitivity, and noise in the diffracted or scattered wave. One of the best materials for holographic recording media is silver halide emulsions, though they are difficult to produce due to thermodynamic instability.[12] Polymers have also been well-established as photosensitive materials, including photoresists, photochromic azopolymers, anthracene-containing polymers, and photopolymers. In the area of inorganic materials for holographic recordings, there are photorefractive crystals such as doped or undoped $LiNbO_3$ (and other niobates[13]) and $LiTaO_3$ (mentioned earlier), barium titanate, and other barium-based titanates. Various molecular weight and doped LC, as well as PDLC with different concentrations of LC or LC droplet morphologies, are also being investigated for holographic recording media applications. Table 2 lists the various materials and the properties of each.

Table 2 Holographic recording materials and their properties (table reprinted with permission of Beev et al. [10])

Material/ Effect	Vol/ Surf	Sensitivity		Storage density	Response time *	Driving voltage**	Δn	Thickness	Stability		
		Spectral range, nm	S cm/J	Lines/mm				μm	Rewritable/ n° of read cycles	Temp range °C	Lifetime
PERMANENT STORAGE											
Silver Halide	V/S	< 1100	> 1100	up to 10000			0.02	7–20	no	< 100	years
Dichromated gelatin	V	< 700	~ 100	> 5000			0.022	15–35	no	< 200	years
Photopolymers	V	514, 532, 650–670	0.5- 6.7 10^3	> 5000			0.012	5–500	no	< 100***	> 10 years
DYNAMIC RECORDING											
$LiNbO_3$	V	350–650 800–1000	0.02–0.1 up to 40	> 2000	0.5–20 s	~ kV/cm	$2\ 10^{-3}$	> 10000	yes	< 500	years
$LiTaO_3$	V	300–550		> 2000	0.1–20 s	~ kV/cm	10^{-3}	> 10000	yes	< 450	years
$KNbO_3$	V	400–900	30–3000	> 2000	1 ms^{-1} s	~ kV/cm	10^{-4}	> 10000	yes	> 50 < 200	years
$Sn_2P_2S_6$	V	550–1100	1000–5000	> 2000	0.5–500 ms	~ kV/cm	$3\ 10^{-4}$	> 10000	yes	< 66	years
Azobenzene LC and amorphous polymers / photo-isomerisation	S/V	488,514, 532, 633	10^2	> 6000	10^2 s		0.1	2–10	yes	< 80 – –120***	years
Azobenzene LC and amorphous polymers / surface reliefs	S/V	244–532	10^2	> 3000	10^2 s		0.1	3–5	yes	< 80 – 120***	years
Photochromics	S/V	vis	$3\ 10^2$	> 1600	ms		10^{-3}	> 100	> 10^6	< 45 – 100***	years
PDLC PIPS / TIPS / Photorefraction	S/V	360–532 770–870	> $3\ 10^3$	> 6000	ms	~ 10 V/μm	0.05	20–100	no PIPS/ TIPS yes PR	> t40–t10 < 50 – 100	years
Dye-doped nematic	S/V	440–514	$3\ 10^3$	0> 1000	ms	0.1 V/μm (PR)	0.1	10–20	yes	< 48 – 95	years
Bacteriorhodopsin in gelatine matrix	V/S	520–640	$4.7{\cdot}10^6$	> 1000	ms		$2{\cdot}10^{-3}$	30–40	> 10^6	–20/40	> 10 years

*Here for dynamic media only (for materials exhibiting permanent storage it is usually the time to obtain any diffracted signal from the hologram)
**Where electric field is employed to switch the structure
***Strongly dependent on the molecular weight and the polymer type.

3. Part II: Volumetric and Holographic Displays

Real-time holography of a live scene, object, or person requires considerable computing resources, including high-resolution cameras, calculation of depth perception using sensors, and accurate and high-rate rendering of the live video.[14] Currently, this is still a significant challenge. However, volumetric and holographic displays using CGH that can be viewed from all angles by multiple viewers have been successfully achieved by many researchers and industry groups. A detailed description of the various volumetric display technology is found in Geng.[4] This section will provide examples of some of these display technologies.

In volumetric displays, voxels of the image are displayed onto a physical medium in 3-D space. Holographic displays are computer-generated images displayed by modulating the light field (the amplitude, direction, and phase), using SLM. Various methods exist for displaying voxels.

One example is drawing a voxel on microbubbles. Kumagai and Hayasaki use a femtosecond laser to excite a high-viscosity glycerin screen by multiphoton absorption. This causes microbubbles to form, and with 3-D laser beam scanning to vary the focal points the volume of voxels renders the high-resolution CGH image.[15] Another technique is to use fog or water vapor as the medium to display the CGH image.[16,17] The fog screen can be adjusted for density to control opacity. Some fog screens used for entertainment can be 2 m wide, and several screens can be "linked" together for a larger image. Some fog screens are essentially 2-D screens projecting a pseudo 3-D image, but others are true 3-D projections. The fog screen created by Zeng et al.[17] is cylindrical, and several kinoforms of the sliced volumetric object are calculated by the slice-based fresnel diffraction algorithm. The 3-D image is reconstructed using an LCSLM and rendered onto the fog screen. Figure 3 shows the schematic of the technique and the cylindrical fog screen apparatus.

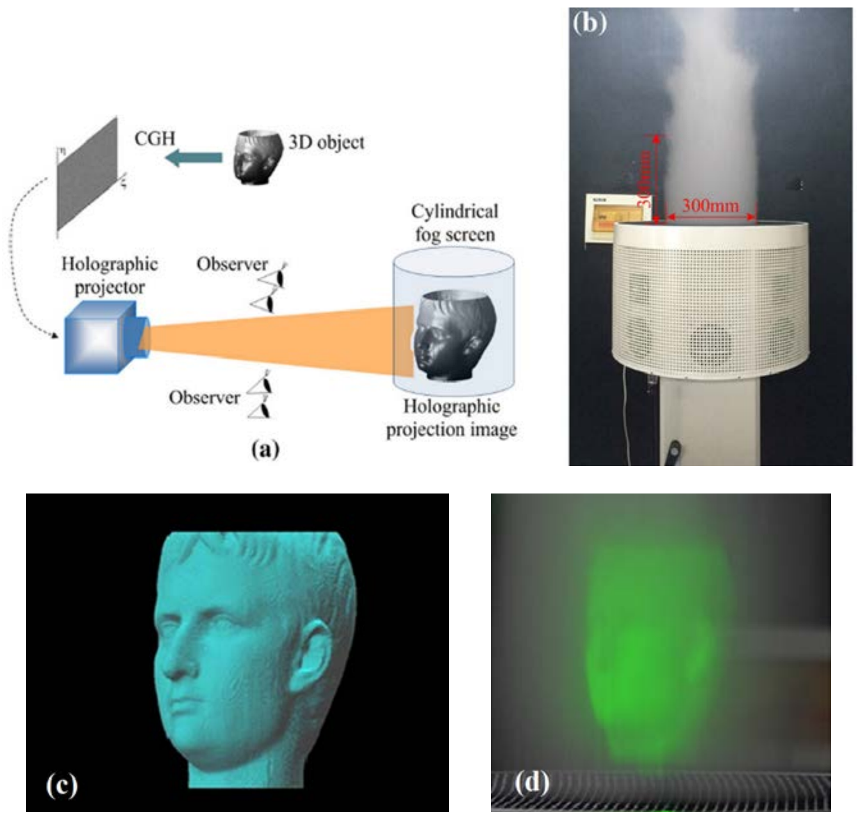

Fig. 3 Volumetric display: (a) schematic, (b) cylindrical fog-screen apparatus, (c) CGH image, and (d) rendered holographic image (images reprinted with permission of Zeng et al.[17])

Instead of using fog as a screen, some researchers are demonstrating volumetric displays with plasma. Saito et al.[18] and Ochiai et al.[19] have rendered aerial 3-D displays using plasma generated by a femtosecond laser. In their system, Ochiai et al. use the laser-induced plasma for the light emission and SLM and scan the laser with a Galvano mirror to render the holographic images. The drawback is that currently the rendered volume is limited to 1 cm^3. However, interaction with the hologram is possible and causes a plasma-generated haptic sensation. A diagram of Ochiai et al.'s setup as well as the rendered image is shown in Fig. 4.

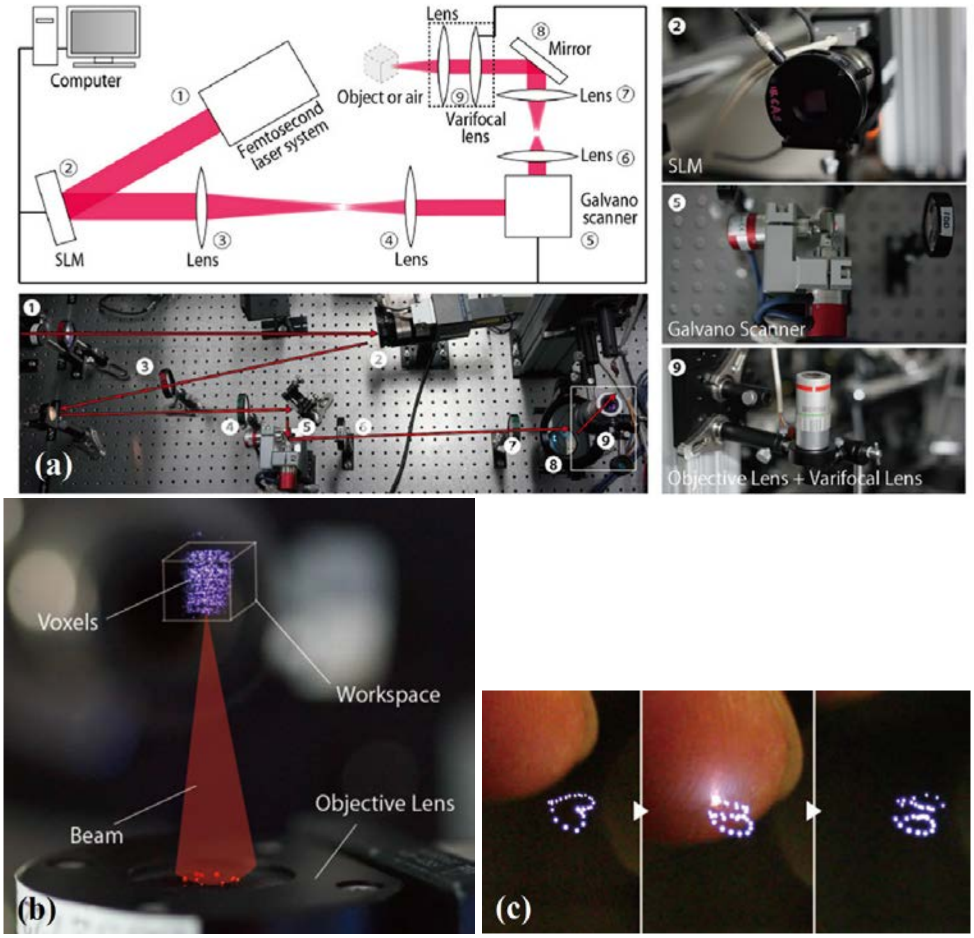

Fig. 4 (a) Drawing and photograph showing the femtosecond-laser-induced hologram setup where (1) is the femtosecond laser; (2) SLM; (3), (4), (6), and (7) lenses; (5) Galvano scanner, (8) mirror, and (9) the objective and the varifocal lens. (b) Photograph showing the projected voxels with illustrations showing the voxel area and the beam emitting the plasma. (c) Rendered heart that, once touched, splits into 2 ovals. (Images reprinted with permission of Ochiai et al.[19])

Another technique is projection of the holographic image in a light field.[19–23] This can be accomplished by several methods. One method used by Miyazaki et al. and Maeda et al. is using a dihedral corner reflector array that converges light from a point light source to a location where the 3-D image is projected.[21,22] Other methods use a screen and multiple projectors[23] or a projector and a moving screen that diffuses the light, creating a light field.[24] The schematic of the moving-screen light-field technique and the resulting holographic image is shown in Fig. 5.

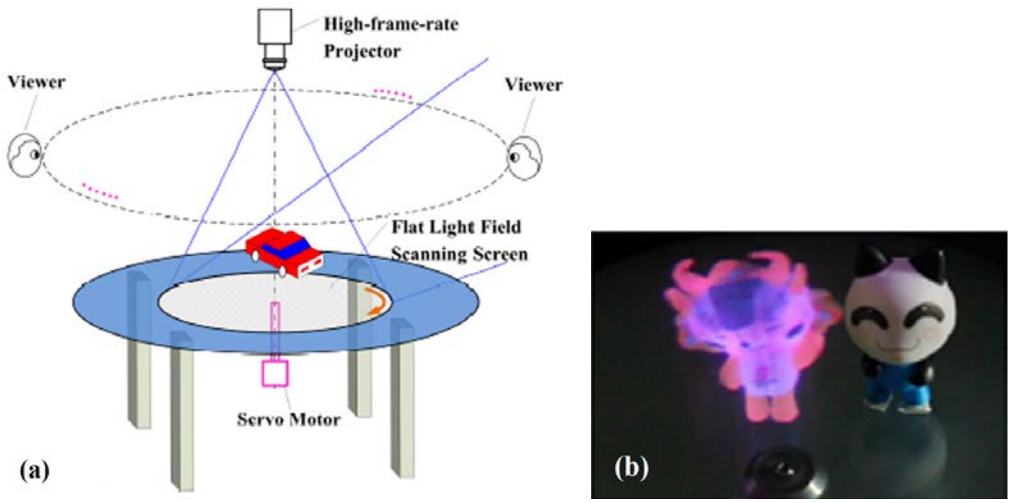

Fig. 5 (a) Light-field display and (b) resulting holograph of a pink doll next to a real panda figure (images reprinted with permission of Xia et al.[23])

There are several commercially available volumetric and holographic displays. One is Voxon's Voxiebox, which uses a laser with a moving screen similar to that of Xia et al.[23] It can project over half a billion voxels of a "moving" image every second into the 18 × 18 × 8 (xyz in cm) volumetric display area. An example of a Voxiebox hologram is shown in Fig. 6. Another is RealView, having the benefit of being interactive, which uses digital holography for displaying full-color images. Figure 7 shows the hologram of a dragon that can flap its wings and be rotated by the viewer. There are many companies working on holographic or 3-D volumetric displays, including Google, Microsoft, Samsung, Intel, Apple, Sony, Qualcomm, Zebra, Leia Display Systems, SeeReal, Heloxica Inc., LightSpace Technologies Inc., and Actuality Systems Inc. Several US universities conduct significant efforts in this area as well, including the MIT Media Lab, the University of Southern California Institute for Creative Technology, and the University of Arizona.

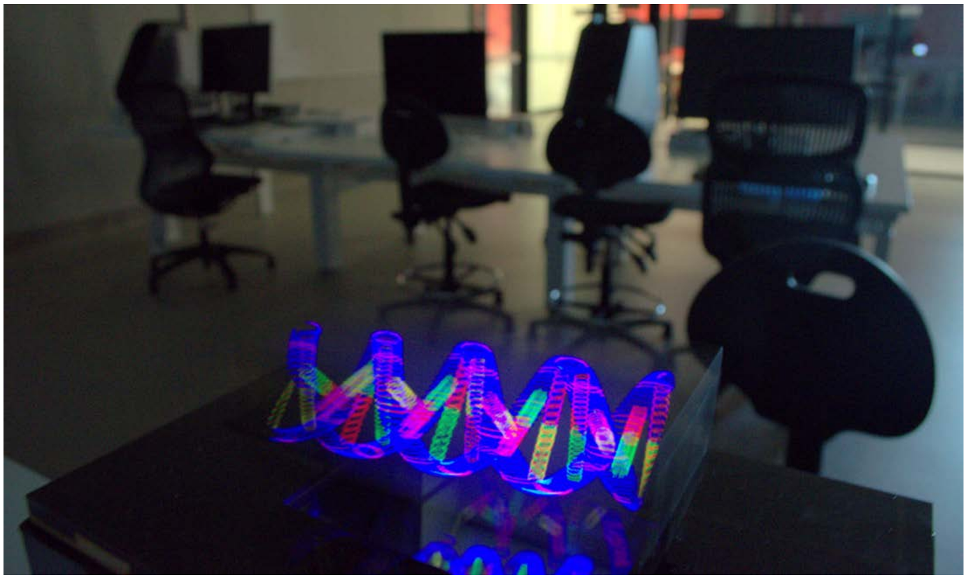

Fig. 6 Example hologram rendered by Voxiebox (image reprinted with permission of Voxiebox[25])

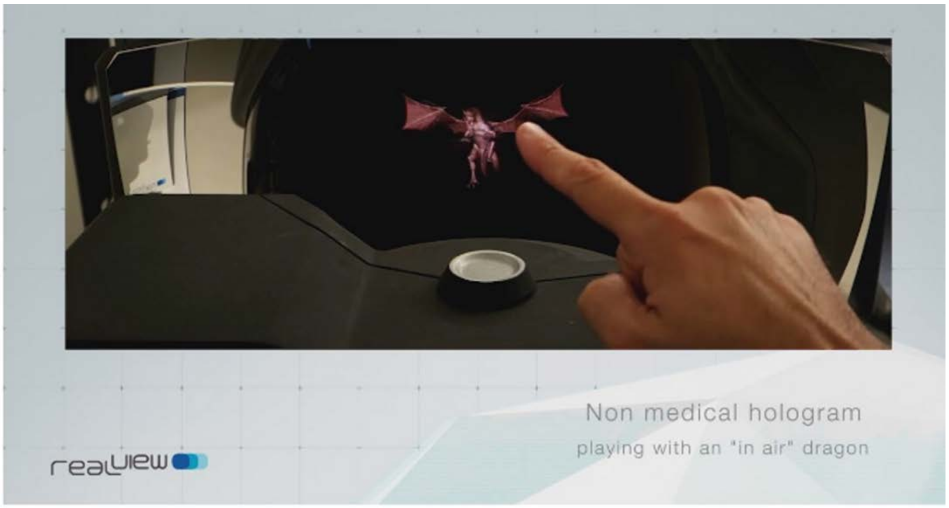

Fig. 7 RealView's interactive dragon (image reprinted with permission of RealView[26])

4. Applications

The current major driver for the holographic and volumetric display technology is for entertainment applications, such as 3-D TV and movies, gaming, and mobile devices. However, development is also underway for applications in the medical industry, marketing and advertising, and training, especially when haptic feedback[27,28] is incorporated into the interaction with the projected image. An area where a holographic technology has already been used, albeit in a pseudo-hologram projected onto a screen, is communication.

However they are used in classrooms, holographic projections have some limitations. A recent, small study in South America evaluated the use of holographic projections in education.[29] Although only 22 students participated in the study, their responses to the use of holographic technology were mixed: 81% stated that they “felt” the presence of the professor when corresponding with the holographic teacher, while 95% of the students accepted the temporary use of a holographic professor in a situation where the professor was not physically available, such as due to travel. However, 58% of the students who attended at least 5 classes stated that the novelty wore off and they began to lose interest. Only 42% of the students believed they achieved the same amount of learning from a holographic professor as from a physical professor.

When holography is applied as part of a learning or training tool, the benefits are clear. For example, in medical training, if students can interact with a realistic hologram of an organ or body, it would enhance their education. If medical students could perform surgery on a 3-D hologram without the risk of harming a real human, this technology would be a clear benefit to society. Similarly, holographic projections and 3-D displays could be used in military training applications. In fact, under the Urban Photonic Sandtable Display Program, the US Defense Advanced Research Projects Agency partnered with Zebra Imaging to produce a prototype of the ZScape Motion Display for a real-time streaming of 3-D holographic battle locations for better planning.[30] Another benefit for military applications is using augmented virtual reality to reduce the cost of training, such as live-fire training, or to recreate difficult situational training scenarios. Recently, the Office of Naval Research’s Augmented Immersive Team Training project, started in fiscal year 2011, produced and transitioned the prototype of a more accurate virtual reality training simulation for the Marines to Program Manager for Training Systems. But this prototype still requires the use of a head-worn display. If this system could be created as an autostereoscopic holographic system, without the need for a cumbersome head-worn display, the training could be more effective.[31]

Other military applications include in-theater deceptive tactics. If the holographic technology advances to where holographic systems could be portable, the display large enough, and the resolution high enough, holograms could be used as camouflage or to augment reality for deception.

5. Conclusions

There is significant growth in the research and development of holographic (and 3-D volumetric) display technology. In fact, a market research report published in 2015 by Markets and Markets on the holographic display market,[32] estimates that the holographic technology market will grow to an estimated $3.57 billion by 2020 and grow at a compound annual growth rate of 30.23% from 2014 to 2020. This growth is expected to be led by holographic technology for medical applications and consumer electronics. Similarly, for the volumetric display market, it is expected to reach $348.2 million by 2020 at a compound annual growth rate of 33.28% from 2015 to 2020.[33] That being said, the maturity of the holographic technology is still in its infancy. Although holographic projections for communications and entertainment have been achieved with a simplified projection onto a 2-D screen, this technology is just an improvement on Pepper's Ghost. This may be sufficient for communication, but we are few years away from applying holography as an effective training tool. For holography to be applied for the military's disruptive augmented-reality applications, more research and development are needed. The resolution of the projected image, the size capability of the projection, and computing power are still lacking. However, this technology is rapidly advancing, and in the not-too-distant future, an interactive holography could be part of in-theater deceptive and camouflaging techniques.

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List of Symbols, Abbreviations, and Acronyms

2-D	2-dimensional
3-D	3-dimensional
Ba	barium
CGH	computer-generated holographic
GWS	guided wave scanner
La	lanthanum
LC	liquid crystal
$LiNbO^3$	lithium niobate
$LiTaO^3$	lithium tantalite
MIT	Massachusetts Institute of Technology
Na	sodium
PDLC	polymer-dispersed liquid crystal
SLM	spatial light modulator
ZBLAN	ZrF4-BaF2-LaF3-AlF3-NaF
Zr	zirconium

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