Ultra-realistic imaging: a new beginning for display holography

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ABSTRACT

Recent improvements in key foundation technologies are set to potentially transform the field of Display Holography. In particular new recording systems, based on recent DPSS and semiconductor lasers combined with novel recording materials and processing, have now demonstrated full-color analogue holograms of both lower noise and higher spectral accuracy. Progress in illumination technology is leading to a further major reduction in display noise and to a significant increase of the clear image depth and brightness of such holograms. So too, recent progress in 1-step Direct-Write Digital Holography (DWDH) now opens the way to the creation of High Virtual Volume Displays (HVV) - large format full-parallax DWDH reflection holograms having fundamentally larger clear image depths. In a certain fashion HVV displays can be thought of as providing a high quality full-color digital equivalent to the large-format laser-illuminated transmission holograms of the sixties and seventies. Back then, the advent of such holograms led to much optimism for display holography in the market. However, problems with laser illumination, their monochromatic analogue nature and image noise are well cited as being responsible for their failure in reality. Is there reason for believing that the latest technology improvements will make the mark this time around? This paper argues that indeed there is.

Keywords: Holographic Display; Color Holography; Display Holography; 3D Imaging, Holographic Window;

1. INTRODUCTION

Modern high-definition flat-screen television displays (HDTV) offer a realism simply unthinkable just ten years ago. Recently many such televisions now even offer the possibility of displaying high-quality three-dimensional images when used in conjunction with special glasses. From a certain perspective today's television technology might well be regarded as falling under the category of "Ultra-Realistic Imaging".[1] However, if one examines the intrinsic information content of today's HDTVs, it is in fact far inferior to that of interferometric displays such as color holograms or Lippmann photographs. This incredible capacity to encode information inherent to interferometric or holographic displays leads to possible applications of this technology which would be extremely difficult to realize using non-interferometric principles. One such application is the holographic window. This is a 3D static or animated digital full-color holographic display of extreme clarity and depth.

Color holograms recorded by analogue or digital methods are becoming more popular thanks to new RGB lasers and panchromatic recording materials. The goal is to be able to record holograms which display the colors of the recorded object as accurately as possible. Over the last few years improvements in the recording and displaying of color holograms have occurred. Two types of holograms exist: the analogue single-beam color reflection hologram and the digitally-printed color reflection hologram. To obtain the most realistic-looking images, reflection holograms are the most suitable. The digitally-printed holograms can be created with selected colors to fit a particular image. For example completely computer-generated holograms of non-existing objects have of course no "correct" colors; the image can have any desirable colors. However for museum and archival applications it is important to record 3D images with extremely accurate color rendering. To some extend this can be achieved in both analogue and digital holograms. New applications of color holography have been reported, which are believed to become more important in the future. To be able to record or print high-quality color reflection holograms it is necessary to use extremely low-light-scattering recording materials, which means the use of ultra-fine-grain silver-halide emulsions. An alternative to silver halide materials are the panchromatic photopolymer materials.

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Analogue color holograms of the Denisyuk type are the ones which really create the illusion of viewing a real object behind the plate rather than an image of it. The possibility to record ultra-realistic holographic images depends on selecting the optimal recording laser wavelengths. Three (RGB) wavelengths are a minimum, but four or five are required for better color rendering.[2] The importance of the recording material is already mentioned. The third factor is the light source used to display the recorded color holograms. The light and the illumination arrangement (source size, distance and angle of illumination) play a very important part in creating ultra-realistic 3D images. The new LED lights have contributed to the progress in displaying color holograms. What do we mean by an ultra-realistic image?

- It looks "identical" to the real object observed by eye
- Very accurate color rendition
- Same scale – no magnification
- Resolution corresponds to the eye resolution
- No detectable image blur
- No field of view limitations
- Image light reflections move like they do on the object
- In principle – recording light waves reflected off an object, store and recreate them later
- ONLY HOLOGRAPHY can accomplish this "Wavefront Reconstruction"

2. COLOR HOLOGRAPHY

To record color holograms at least three laser wavelengths (RGB) are needed. However for perfect color rendering more than three wavelengths are required.[2] The lasers must be powerful, with long coherence and very stable output power. Both vertical and horizontal parallax are desirable when recording holographic ultra-realistic images. This means that the most suitable analogue recording setup is the single-beam Denisyuk technique. Digitally-printed color holograms can also be created with both vertical and horizontal parallax, but most of the current ones are with horizontal parallax only. So far, hologram recording has mainly been performed in a laboratory, however to make it easier for museums to use holography, there is a demand for transportable recording equipment which is now available. Since many artifacts cannot be moved to an existing laboratory it is important to perform the recording at the museum. Thanks to new powerful DPSS lasers it is now possible to make such mobile recording equipment possible. It is possible to get red, green and blue lasers with high output power and long coherence length. Examples of current CW lasers on the market are the Cobolt DPSS lasers.[3] The new lasers are now capable of 0.5 W to 1.5W output power depending on wavelength. A company with suitable lasers is Coherent[4] with the new range of high-power optically-pumped semiconductor lasers. Laser Quantum[5] is another manufacturer of lasers to be used in movable equipment.

2.1 Analogue color hologram recording setup

The principle of recording analogue color holograms of the Denisyuk type is shown in Fig. 1. In the setup only three lasers are indicated, but it is possible to add one or two more lasers using additional beam combiners. This is the setup which is used in holographic laboratories equipped with large, often water-cooled argon-ion and krypton-ion lasers.

2.2 Mobile recording equipment

Gentet and Shevtsov[6] reported about a camera for recording color holograms to be used with the Ultimate glass plates up to the 30 cm by 40 cm format. The camera is equipped with a red (λ= 639 nm) semiconductor laser and two solid-state lasers, a green (λ = 532 nm) and a blue (λ = 473 nm).

The Hellenic Institute of Holography (HiH)[7] in Athens has produced a transportable camera, the Z3^{RGB} also referred to as ZZZyclop™.

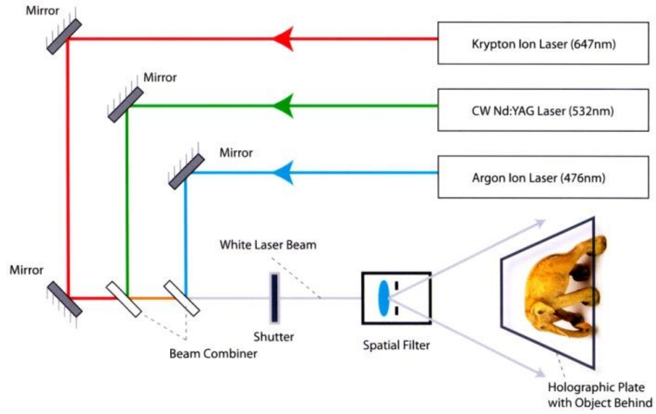

Figure 1. Setup for recording analogue color reflection holograms

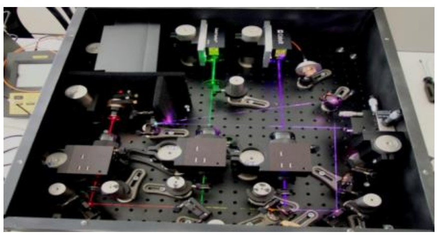

Figure 2. The lasers inside the camera

Figure 3.The ZZZyclop™ camera

The inside of the camera is shown in Fig. 2. The Z3^{RGB} camera is a computer-controlled opto-mechanical device capable of exposing selected, commercially available or experimental, panchromatic silver-halide emulsions to combined red, green and blue laser beams. The device consists of a main camera unit (MCU) built on top of a lightweight aluminum honeycomb and a control electronics unit (CEU). Three solid-state lasers (Crystal and Cobolt lasers) are used in the camera with TEM_{00} emissions with coherence lengths of more than five meters each. The MCU contains suitable optics to generate a clean colinear mixed RGB beam. The ZZZyclop™, shown in Fig. 3, has been successfully used to record artifacts in Greek museums. HiH has also produced a portable darkroom for on-site processing. More details about HiH are provided in a publication by Sarakinos *et al.*[8] and in paper 9006-3 at this conference.

2.3 Commercial panchromatic recording materials

Currently the main panchromatic recording materials are the silver-halide materials and photopolymer products.

Table 1: Commercial silver-halide holographic recording materials for color holograms

Material	**Spectral sensitivity** [nm]	**Resolving power** [line pairs/mm]	**Grain size** [nm]	**Substrate**
Colour Holographic				
RGB: BB-PAN	440-650	6000	10	Glass
Slavich				
Pan: PFG-03C	450-700	6000	10	Glass/Film
Sfera-S				
Pan: PFG-03CN	435-665	6000	9	Glass/Film
Ultimate				
Pan: 08-COLOR	460-650	10000	8	Glass/Film

2.3.1 Silver-halide materials*.* The market offers a very limited choice of commercial silver-halide recording materials for color holography. Two Russian companies have holographic emulsions suitable for recording color holograms. SLAVICH Joint Stock Company[9] and Sfera-S[10] are both located in Pereslavl, outside Moscow. Panchromatic materials for color holograms are manufactured by *Slavich* under the name of PFG-03C. *Sfera-S*, located in an ex-Slavich building, is now manufacturing a high-quality emulsion PFG-03CN for color holography which is available coated both onto glass plates as well as onto film. The main customer is Geola Digital uab[11] in Vilnius, Lithuania. The Sfera-S emulsion[12] is sensitive to the short laser-pulse recording which makes it suitable for pulsed RGB digital holographic printers. Both the Slavich and Sfera-S materials are available from Geola or from their international network of distributors.

Colour Holographic Ltd[13] is the primary UK manufacturer of ultra-fine-grain holographic emulsions. Their RGB BBPAN emulsion is of very high quality. Manuel Ulibarrena is responsible for the new materials including their new applications of color holography. Michael Medora's production facility is based in Maldon, Essex, UK.

The other European manufacturer of panchromatic emulsions is *Ultimate – Holography* in France.[14] The Ultimate ultra-fine-grain emulsion is based on the initial work by the Gentet brothers.[15] Today Malasy Gentet (Yves Gentet's wife) is responsible for the manufacturing of the holographic plates. Her expertise in the field of silver halide-emulsions introduced a new achievement in quality control and reproducibility of Ultimate materials, including major improvements in their storage lifetime. The plates are manually produced with extreme patience and care. However the production capacity of such plates is limited. Commercial silver-halide holographic recording materials for color holograms are listed in Table 1.

2.3.2. Photopolymer materials*.* Photopolymer materials can be used for recording phase holograms, where applications in the mass production of small (usually monochromatic) security and display holograms as well as optical elements constitute today the main commercial interests. The sensitivity is not as high as the silver-halide materials but the advantages are a low light-scattering noise level as well as an innate suitability for the application of dry processing techniques.

E. I. du Pont de Nemours & Co.[16] has been the main manufacturer of commercial photopolymer materials and has for a long time marketed these under the name of *OmniDex*®. Since 1995 DuPont has manufactured a panchromatic material for color holograms.[17-19] Initially DAI Nippon Printing Co., Ltd. (DNP)[20] used the DuPont panchromatic material for producing photopolymer color holograms.[21,22] More recently, DNP in conjunction with *Nippon Paint Co., Ltd.*, has developed a new photopolymer material which is now used for manufacturing mass-produced volume reflection holograms. Nippon Paint is responsible for materials development, while DNP is responsible for the development of the production technology.

The Bayfol®HX[23-25] by *Bayer MaterialScience AG*[26] intended for color holography requires less post-processing as compared with the DuPont materials. The material has many advantages such as long life time, stability, almost no shrinkage and no post-processing (thermal or wet). Since the Bayer photopolymer materials require no subsequent chemical or thermal treatment they are exceptionally suitable for cost-effective mass-production of volume holograms. The Bayer photopolymer has the real potential to become a leading material for light management within a variety of new technologies - for example in improved 3D digital and analogue holographic displays or for diffusers required in energy-efficient lighting technologies such as LEDs. However, like DuPont which restrict their materials for their in-house hologram production and document security producers, Bayer has decided, at least for the moment, to restrict sales of its holographic materials in order to protect the value chain to the security industry.

Polygrama[27,28] in Brazil is another manufacturer of holographic photopolymer materials. Polygrama *DAROL* photopolymer is a dry film for holography which is provided with adequate resolution, high contrast and low scatter. It records a reflection hologram that must be thermally developed in a single process to deliver a hologram with high diffraction efficiency. It is totally moisture resistant and stable. A new panchromatic material was introduced in 2013. The DAROL films are available as 20 x 10 cm sheets with a 30-40 µm thick photopolymer onto optical clear polyester with laminated thin PET or HDPE cover. The panchromatic polymer sensitivity is peaked at 476 nm, 532 nm, and 640 nm with a sensitivity of 5–30 mJ/cm². Thermally developed reflection holograms have a high $\delta n \leq 0.08$. Lynx in Brazil is distributing the *DAROL* film.[29] A new company has been established in the USA: Polygrama Inc. with a R&D and production facility in Florida.[30]

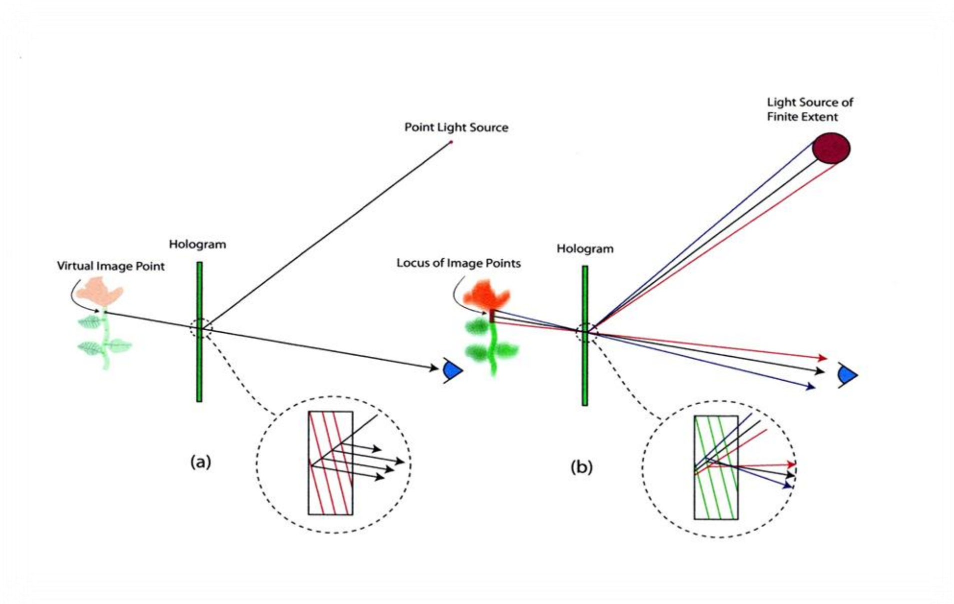

Figure 4. Image blurring in a reflection hologram when illuminated with an extended light source

3. DISPLAY OF COLOR HOLOGRAMS

Often the term "*reconstruction*" is used to describe the display of a hologram. This refers to the fact that if the reference beam, which was used to record the hologram, is used to also illuminate the processed hologram plate, the wavefront emitted from the object during recording, will be faithfully *reconstructed* generating the holographic image. This underlines the critical fact that in order to obtain a faithful holographic reconstruction, the properties of the reference recording and reconstruction beams must usually be identical. The illumination of holograms is nevertheless a topic which is seldom included in books on holography; but it is as important as techniques to record holograms. Remember that holography is a *two-part process* where the holographic plate, with its recorded interference pattern, constitutes only one of the two parts needed to create the holographic image. The second part is the reference light which is used to display the hologram. The characteristics of this reference light fundamentally control the display process. Only if the properties of the reference and replay lights are identical (spatial coherence, ray divergence, angle of incidence and wavelength) will a distortion-free, correct holographic image be generated. In most practical situations it is rare that the replay light is *absolutely* identical to the recording light. In particular conventional broadband white-light sources are frequently used to illuminate reflection holograms. Here one uses the wavelength selective properties of the reflection hologram to filter out light having a different wavelength to that of the recording light. Illumination by a broadband source will bring with it chromatic blurring and in general the clear image depth of the hologram will be compromised. One of the most important properties of any light source used to illuminate a hologram is spatial coherence. When a hologram is recorded, the reference laser light emanates from a spatial filter having a diameter of between 10 and 25µm. This is several orders of magnitude smaller than the source size of current popular illumination sources. For example, halogen spotlights commonly used to display reflection holograms, have source sizes from one to several centimetres. A finite spatial coherence in the reconstruction source leads to source-size blurring (see Figure 4), which limits the clear image depth of the hologram. For ultra-realistic holographic imaging a rough rule is that the reconstruction source size must be less than 1mm in diameter for every 1m of diagonal distance which separates the illumination source and any point on the hologram. This ensures that any residual source-size blurring will be below the perception level of the standard human observer - as the average human eye can resolve image details of about one millimetre at a distance of 1m. Many applications of color holography require that the display and illumination techniques are carefully considered to display ultra-realistic images. The new LED lights make it possible to reduce the image source-size blurring as well as to improve color rendering.

Figure 5. The *HoLoFoS* LED spotlight

3.1 Light-emitting diodes (LEDs)

The past few decades have seen a continuing and rapidly developing race among manufacturers of LEDs to produce ever cheaper and ever more efficient illuminants. This process is now producing a fundamental transformation in the field of general lighting. These miniature semiconductor devices will undoubtedly lead to the obsolescence of the common incandescent light bulb in the near future. This rapid progress in solid-state LED lighting has opened up new possibilities to illuminate color reflection holograms. A significant advantage of LEDs is that they possess a much smaller bandwidth than broadband white-light sources. Although typical bandwidths are much larger than those commonly associated with lasers and laser diodes, LED light sources should nevertheless be matched to the recording laser wavelengths (or vice versa). This guarantees that only the white light from the LED source (which is a mixture of the primary LED wavelengths) contributes to creating the holographic image. Using a halogen spotlight, a large part of the light spectrum emitted illuminates the surface of the plate without having any impact on the intensity of the image. Instead this light is scattered, lowering the image contrast. The lack of this scattered light in LED illumination can lead to significantly higher image fidelity. In addition LED light sources have considerable advantages over halogen and other traditional lighting sources, such as long life, small size, small étendue, high durability and robustness to thermal and vibration shocks, low energy usage/high energy efficiency, no IR or UV in beam output, directional light output, and digital dynamic colour control – white point tuneable.

3.2 LED spotlights for color holograms

HiH has developed a special LED spotlight for the display of color holograms. The *HoLoFoS* LED spotlight, based on Cree LEDs, is manufactured at AutoTech[31] and is commercialized by TAURUS SecureSolutionS Ltd.[32] Through proper choice of the component LEDs in terms of bandwidth and wavelength, the *HoLoFoS* LED spotlight is capable of achieving high quality reproduction of deep color reflection holograms. The device consists of an illuminating head, extending arms and a mounting base. The illuminating head contains the RGB LEDs, mixing optics, lenses and heat sinks. The system has an embedded microcontroller for intensity control of each LED with DMX-protocol decoding and a miniature wireless receiver. Remote adjustment of the color mixing by DMX-protocol communication is achieved by a handheld wireless remote control. A small switching power supply provides the power needed for EU or US mains. The optics incorporated in the unit provide for an axial mixing of the LED beams resulting in a homogeneous color mixing over the full extent of the projected beam. The small footprint of the LED die (approx. 2 mm) is small enough to produce clear and deep holograms even at small illuminating distances. The illuminating head can be fitted with a variety of LEDs at selected wavelengths and more than three different LEDs can be fitted to match various recording wavelengths. For example, an RRGGBB configuration can be achieved. This is important for color holograms which will be recorded with four or five laser wavelengths to obtain more or less perfect color rendering. Details on the *HoLoFoS* system was presented by Sarakinos *et al*.[33] and more recent information at this conference in paper 9006-3. The current product, shown in Fig. 5, uses three LEDs with the following spectral characteristics for the red, green and blue LEDs which correspond to the lasers of the ZZZyclop™ Camera. The dominant wavelengths for the LEDs are 620 – 630 nm, 520 – 535 nm, and 450 – 465 nm.

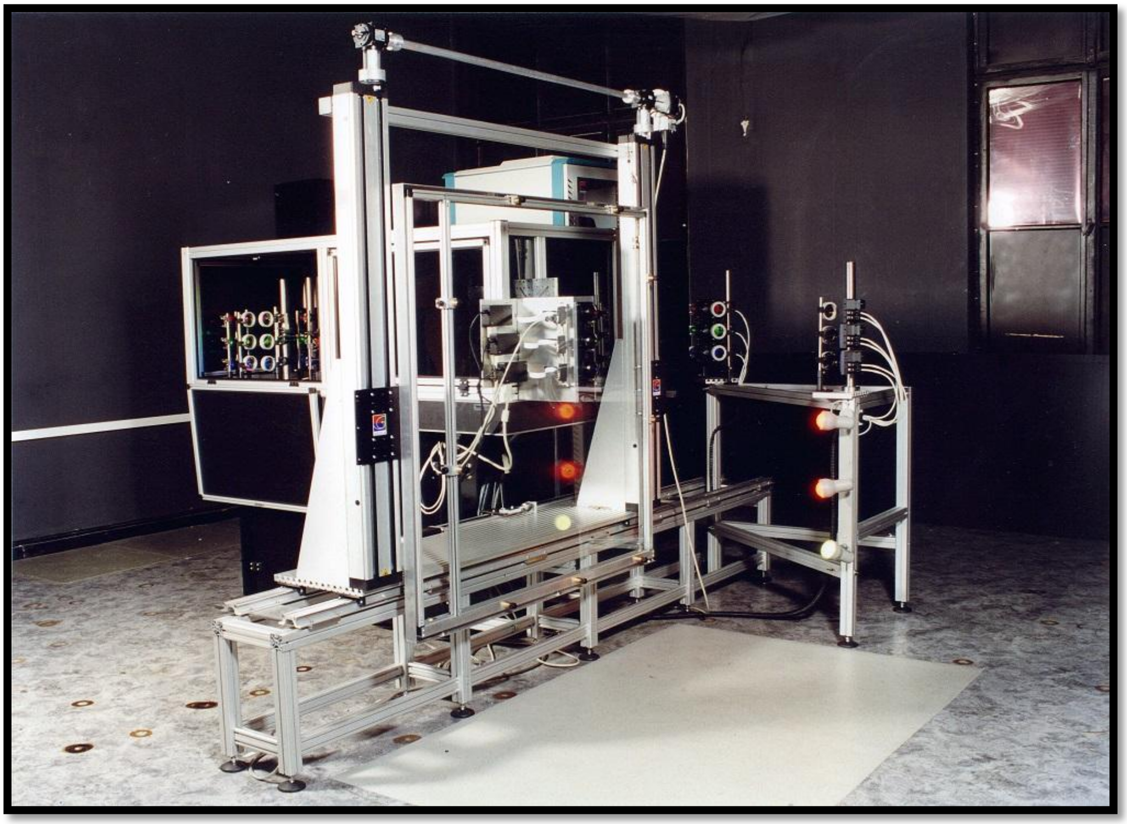

Figure 6. Hologram printer by *Geola*

4. DIGITALLY-PRINTED COLOR HOLOGRAMS

Modern digital holography printers make use of a number of major improvements over the earlier systems.[34] Small RGB pulsed lasers are used to solve the stability problems inherent to the use of CW lasers. The hogel is usually formed using an optical system rather than relying on a contact aperture combined with a projection/diffusion scheme. This then allows the step-and-repeat plate movement system to be replaced by a constant velocity system. Such lens systems create the hogel optically by focusing the light transmitted by the spatial light modulator into a narrow waist. The light distribution at the hogel then effectively becomes the Fourier transform of the distribution at the SLM. Such lens systems can also create a greatly enlarged image of the SLM downstream of the Fourier plane.

The use of nanosecond pulsed lasers in the printers can completely solve the problems of interferometric stability and low printing speed. This is of fundamental importance as it means that small power lasers may be used to print large holograms in reasonable times. With a pulsed laser, the holographic exposure is effectively done in such a small period of time that there is no need to let the system settle. However, some of the best photosensitive materials for color holography are not properly sensitive to nanosecond laser pulses. The Sfera-S material is specially optimised to be used in holographic printers equipped with pulsed lasers.

Very large-field-of-view of color holograms is difficult to obtain in digitally-printed holograms. It is defined by the conic angle of convergence of the focused light forming the hogel. Usually this angle must be large - of the order of 100° if the hologram is to be viewed from a variety of positions. This means that the numerical aperture of the Fourier transform optic must be very large. But as the numerical aperture increases, optical aberrations increase rapidly. And these aberrations act to decrease the resolution of the optical system, which in turn induces image blurring into the final hologram.

Most printers are limited to producing horizontal parallax only holograms. Such holograms require much less memory storage and this allows a simplified computer system to be employed with image files being uploaded over a network. Holograms are created using perspective view information which is generated either from a *Holocam*[35] or through commercially available computer modeling programs. A Geola hologram printer is shown in Fig. 6.

5. APPLICATIONS OF COLOR HOLOGRAMS

Despite holography now being over sixty years old, many of the ultra-realistic display applications are in an early stage of market development. This is really because the color holography improvements have in many cases only recently led to a positive market response. The main applications are:

- Museum artifacts
- Advertising and marketing of expensive products
- Holographic maps, architectural and military
- Forensic applications
- Oil painting reproduction
- Holographic art

5.1 Museum applications

In the days of the British Empire, museums filled their collections with exotic items from around the world. British museums today still possess large collections from foreign countries. But there is increasing pressure to repatriate priceless artifacts to their respective homes. Holography now offers the possibility to essentially duplicate such artifacts - and to a point where an observer practically cannot tell whether he is looking at the real exhibit or at a holographic copy. Although such holographic reproduction can never match the value of actually possessing the real artifact, it can allow the museum to fulfil one of its most important functions - to maintain display of the exhibits. Analogue holography does offer a means to preserving a faithful visual recording of unprecedented microscopic detail. Holography can also help museums with travelling exhibitions as we shall see below. It is difficult for some people to travel to museums and as a result there is pressure on museums to take exhibits to the people. But transporting priceless artifacts is both hazardous and expensive. Transporting holographic copies on the other hand is not. A reason why ultra-realistic color holograms are useful to museums is related to insurance costs of even exhibiting within a museum. Most museums have large collections "downstairs" which they do not exhibit. The reason is that it generally costs more to exhibit something than to securely store it - as the risk of damage or loss is greater when an exhibit is on display. Again holography can help solve this problem. If the hologram is indistinguishable from the real exhibit, why not just securely store the real item and display the hologram?

It should be mention that digital holographic printing can also be usefully applied to museum recordings. Although the resolution of this type of hologram is less than that of an analogue hologram, at the smallest hogel sizes now available (around 250 microns), it can be very difficult for an observer to tell the difference between an analogue and digital hologram with the unaided eye. And the digital hologram offers several sizeable advantages.

5.2 Museum applications in United Kingdom

'Bringing the Artifacts Back to the People' was an important early color holography project which was carried out at the Centre for Modern Optics (CMO) in North Wales.[36] The project involved collaboration with a number of major museums. Color holograms of various artifacts were recorded at the CMO laboratory using the analogue technique described above. The recorded holograms were displayed as a travelling exhibition which toured North Wales and its borders. One of the recorded artifacts, supplied by the British Museum, was a 14,000-year-old decorated horse jaw bone from the ice age, or late glacial period, in Britain.[37] A photo of the hologram is shown in Fig. 7. In total, ten color holograms of different artifacts were included in the touring museum exhibition. Another example is the *Tudor Owl Jug* and the *Sergeant at Arms Ring* hologram, a photo of which is shown in Fig. 8. The two artifacts in the hologram are from the Grosvenor Museum in Chester.

Colour Holographic Ltd. [31] in London has also recorded color holograms from UK museums. An example is the recorded holograms of artifacts from the Birmingham Museum. They recorded color holograms of the front and back of the *Ushabti Figure* (mummiform funerary figure) of the *Princess Nesitanebashru* (c. 1000 BC) found in the cache of Royal Mummies, Deir el Bahari, Thebes, in 1881.

Figure 7. The *Horse Jaw* hologram

Figure 8. The *Owl Jug* and the *Ring* hologram

Figure 9. The mobile museum recording setup

Figure 10. An *OptoClone*© by HiH

5.3 Museum applications in Greece

The most recent HiH activities have been reported by Lembessis.[38,39] The exhibition ***'Heaven and Earth': Art of Byzantium from Greek Collections*** features some 170 rare and important works, drawn exclusively from Greek collections. The exhibition offers a fascinating glimpse of the soul and splendor of the mysterious Byzantine Empire. Recognized masterpieces, many never lent before to the United States, will be on view with newly discovered and previously unpublished objects from recent archaeological excavations in Greece. This exhibition is on display at the National Gallery of Art, Washington DC, between October 6, 2013 and March 2, 2014. After that it travels to the J. Paul Getty Museum in Los Angeles to be on display there between April 9 and August 25, 2014. For this exhibition several color holograms (coined *OptoClones*© by HiH) were recorded by HiH using the mobile equipment with the principle setup shown in Fig. 9. The laser light from the ZZZyclop is directed via a mirror to illuminate the object at an angle of about 45^{o} from above. For the recording the plate is inserted in front of the object. A photo of one of the recorded color holograms is shown in Fig. 10. These holograms were not sent to the USA but instead they are on display at the museum in Greece to replace the artifacts which are temporary gone. A statement by Nikos Konstantios, Archaeologist at *Byzantine & Christian Museum* in Athens is quoted here explaining the reason why he selected the new holographic 3D imaging technique: "We have opted to use display holograms -- instead of digital media - for the visual replacement of selected cultural artifacts during their temporary loan as we felt that their **one-to-one ultra-realistic 3D optical representation** through full-color holography allows the viewer to form an accurate view of the object – even when the original artifact is not present. Moreover, this happens instantly at first glance without any interaction or complications introduced by the digital media (touch screens, buttons, image quality, etc.)"

5.4 Printed color holograms

The main companies currently active in the area of digital holographic printing are *Zebra Imaging Inc*.[40] in the USA and *Geola Digital UAB*[11] in Europe. Zebra was the first company to produce digital color holograms using CW lasers, hogel by hogel. Geola was then the first group to do this using RGB pulsed lasers. Until recently XYZ Imaging Inc, originally a spin-off from Geola, and subsequently operated under the name of RabbitHoles Media Inc, also operated a digital holographic printing facility in Canada.

5.5 Holographic maps

Horizontally-mounted digital full-parallax color reflection holograms with overhead illumination (HMOI holograms) are useful for a variety of applications in mapping and architectural design. Large full-parallax holograms may be laid out on a table and viewed by a group of people. 3D terrain can project up out of the hologram and viewers can easily perceive the 3D structure of mountains and valleys. Such holograms can potentially be rolled up into tubes and taken out for display when required. During several years Zebra has been supported by US military contracts. The main work is for special military applications to produce holographic maps to be used both in headquarters as well as in the field. More information about Zebra and the latest applications have been published by Klug.[41]

HiH has also produced map holograms for geographical services of various national armies, including the Greek Army. The Institute recently cooperated with the NATO Fast Deployment Unit for the Balkan areas based at the city of Thessaloniki (NDC-GR) in the making of one trial map. In this case geographical data, which were freely available on the web, were used (color satellite terrain picture of an area near river Evros in Northern Greece). HiH also reported that they have originated a color holographic map of the island of Kos in Dodecanese on commission from the *Greek Infantry Geographical Services* using real GIS data. The HiH hologram maps have been printed by Geola. Turkey military has shown an interest in topographic reflection holograms created by *General Command of Mapping* in Ankara.[42] These holograms have also been printed by Geola. Park, *Hangyo International Corp*., South Korea, reported on different types of holographic maps.[43]

5.6 Other applications

Among other potential applications of ultra-realistic imaging one can mention forensic applications (preserving evidence which may decompose, deteriorate or decay over time). Oil painting reproduction is another application that can become important in the future which, however, requires perfect color rending to become accepted in the art world.[44] Artists, interested in the holographic technique, have already been attracted to investigate the new ultra-realistic imaging possibilities.

6. HOLOGRAPHIC WINDOWS

A physical window is something which we all take for granted. However the window is a very different thing from a high-definition television display. The light-field surrounding a window is generally extremely complex – simply because the light traversing the window emanates from three-dimensional objects which are themselves complex. As a viewer approaches a normal television screen the picture rapidly defocuses and close-to we observe the pixels rather than a picture. In a 3D-enabled television, as we approach the screen the perspective becomes completely erroneous. But as we approach a window's surface our eyes simply focus through the window to view, in perfect clarity, the objects behind. It is clear that the current techniques of digital holography known today are very close to the point of being able to realise such holographic window displays. Large format digital holographic windows are not the only application of ultra-realistic imaging as promised by interferometric techniques. Archival and display of museum artefacts are for example growing problems which could be addressed by holography. High-definition full-colour holographic displays now have such a realism that it can be extremely difficult to tell whether the object in question is a holograph or indeed the real-thing. Museums often cannot afford to display their collections due to insurance costs and in addition priceless items are all too often damaged when transported to exhibitions. Next-generation holographic technology promises to offer real solutions to these problems and to bring the realism of important and interesting museum collections to more people.

Closely related to the concept of the holographic window is holography's ability to create space. A super-realistic hologram can effectively create virtual space behind its glass surface. Holographic windows and super-realistic holographic displays will undoubtedly find a future market in architecture. Such displays may also be expected to find applications in museums. Imagine for example, going to the British Museum and seeing the pyramids in full-scale through a giant window display. And since such displays are intrinsically digital, one is not constrained to modern landscapes of course. So real scale super-realistic images may be created of historical events. Even limited animation of the image may easily be included in such displays. The larger the display the easier such animation is to encode and the longer it can be. Clearly, holographic windows or super-realistic high-virtual-volume displays require digital full-parallax writing techniques such as DWDH. Analogue holograms could not in any form or manor be expected to generate such high virtual volumes. Today's digital printers have not yet targeted HVV displays; these printers are capable only of producing digital holograms of rather limited depth. The actual depth possible depends on the field of view that the printer is required to create in the printed hologram. When field of view is maximized, the capacity of the hologram to reproduce large depths falls. Up until now this has not been important as typical illumination sources introduced greater blurring into the hologram than any restriction due to the printer's optical construction. HVV and holographic window displays primarily require improvements in the current digital holographic printing technology. No printer has the required resolution today. However, the modifications necessary are certainly feasible, even with today's technology. The illumination and materials technologies are also here. This is a real application of ultra-realistic imaging which appears to be well within reach, but remains unrealized today.

7. CONCLUSION

The virtual color image behind a holographic plate represents the most realistic-looking 3D image of an object that can be recorded today. The extensive field of view adds to the illusion of beholding a real object rather than portraying a mere image. Good color rendering can be achieved through choosing the optimum recording laser wavelengths within the visible spectrum. The application of color holography in museums and the tourist industry alike could exploit this new 3D imaging technique. Recording the museum objects as 3D color holograms allows the image of an object to leave a museum, increasing the number of people who can experience the history of the object and its place within our culture.

Large format 3D color digital holographic displays can be extremely impressive. Over the years this application has had a number of false starts due to a variety of reasons - mostly connected with color issues, reliability, speed of fabrication, illumination and price point. From time to time great interest has been shown by advertising agencies, printing companies and by organisations wishing to promote their products. Many of the issues which have frustrated penetration of holographic displays in the advertising display sector are now being resolved. Advances in laser technology are making the process of writing the holograms easier. Better materials, such as the new photopolymer materials, allow higher quality and cheaper images to be produced. And advances in illumination technology make the final hologram brighter, deeper and easier to light.

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