Ultra-realistic 3-D imaging based on colour holography

H I Bjelkhagen

Hansholo Consulting Ltd., The Bungalow Offices, St-Asaph, LL17 0LQ, UK
E-mail: hansholo@aol.com

Abstract. A review of recent progress in colour holography is provided with new applications. Colour holography recording techniques in silver-halide emulsions are discussed. Both analogue, mainly Denisyuk colour holograms, and digitally-printed colour holograms are described and their recent improvements. An alternative to silver-halide materials are the panchromatic photopolymer materials such as the DuPont and Bayer photopolymers which are covered. The light sources used to illuminate the recorded holograms are very important to obtain ultra-realistic 3-D images. In particular the new light sources based on RGB LEDs are described. They show improved image quality over today's commonly used halogen lights. Recent work in colour holography by holographers and companies in different countries around the world are included. To record and display ultra-realistic 3-D images with perfect colour rendering are highly dependent on the correct recording technique using the optimal recording laser wavelengths, the availability of improved panchromatic recording materials and combined with new display light sources.

1. Introduction

This paper is concerned about *colour holograms* which, after the recording process (by analogue or digital methods) and upon processing, display the colours of the recorded object as accurately as possible. There are many techniques of creating holograms displaying different colours, e.g. *pseudo-colour holograms*, which have been popular among artists over many years. However they are not creating holograms of objects in their correct colours and not included here.

Over the last few years it has become popular to produce computer-generated colour holograms. In this case there is a possibility to first record a scene or an object photographically, e.g. using a camera moving along a horizontal rail. Large quantities of 2-D colour images of the object are captured during the recording. Then the images are transferred into a computer-generated pixilated printed hologram. If the hologram is of the reflection type the colour of the image remain fixed and is independent of viewer position. By using the rainbow technique it is possible to produce transmission colour holograms, however, the correct image is only possible to view at a certain position. Any deviation from the viewing position changes the colours of the holographic image. Therefore, to obtain the most realistic-looking holographic images, reflection holograms are the most suitable. The digitally printed holograms can be created with selected colours to fit a particular image. For example completely computer-generated holograms of non-exciting objects have of course no "correct" colours; the image can have any desirable colours. However for museum and archival applications it is important to record 3-D images with extremely accurate colour rendering. To some extend this can be achieved in both analogue and digitally-printed holograms, however improvements are needed in both recording techniques as well as recording materials.

The focus here is on the direct holographic recording of objects to create colour-accurate hologram images. To be able to record or print high-quality colour reflection holograms it is necessary to use extremely low-light-scattering recording materials, which means the use of ultra-fine-grain silver-halide emulsions.[1-6] This type of material has the advantage of higher sensitivity compared to photopolymer and dichromated gelatin (DCG) which are used as alternative materials for colour holography.

Table 1: Total average error for three to seven optimal wavelengths

Number of wavelengths	Optimal laser wavelengths (nm)	Average colour rendering error*
3	466, 545, 610	0.0137
4	459, 518, 571, 620	0.0064
5	452, 504, 549, 595, 643	0.0059
6	451, 496, 544, 590, 645, 655	0.0040
7	445, 482, 522, 560, 599, 645, 655	0.0026

* Computer simulation based on the *Macbeth ColorChecker*® target used to illustrate improved colour rendering with increased amount of laser wavelengths, assuming a perfect recording material.

2. The progress of colour reflection holography

In several publications details and the history of colour holography have been provided.[7-12] Analogue colour holograms of the Denisyuk single-beam reflection type, are the ones which really creates the illusion of viewing a real object behind the plate rather than an image of it.

The possibility to record super-realistic-looking holographic images depends on four factors:

- The recording laser wavelengths;
- The recording setup;
- The recording material;
- The light source used to illuminate the recorded hologram.

In regard to required laser wavelengths at least three laser wavelengths (RGB) are needed, However for perfect colour rendering more than three wavelengths are required.[10,13,14] In **Table 1** three to seven optimal laser wavelengths are listed based on computer simulation to minimize the colour rendering error. The *Macbeth ColorChecker*® target was used to illustrate improved colour rendering with increased amount of laser wavelengths, assuming a perfect recording material which means that the selection of wavelengths is actually independent of the holographic recording process. Bazargan [15] is addressing the laser wavelength selection issue at this conference.

The lasers must be powerful, with long coherence and very stable output. If one wants the most realistic-looking images, parallax in both vertical and horizontal directional are desirable. This combined with a viewing field of 180-degrees in both dimensions means that the most suitable direct-recording setup is the single-beam Denisyuk technique. Digitally printed colour holograms can also be created with both vertical and horizontal parallax to make them more realistic looking. In the following both types of colour reflection holograms are described with recent progress and applications. The quality of the recording material is extremely important to obtain realistic-looking holographic colour images. The current problem is very limited supply of suitable commercial materials for colour holography.

2.1. Commercial recording materials for colour holography

The choice of recording material is of equal importance as the choice of laser wavelengths for the recording of a colour hologram. To be able to record high-quality colour reflection holograms it is necessary to use extremely low light-scattering panchromatic recording materials. Currently the main materials in use are special emulsions based on silver-halide and photopolymer materials.

2.1.1 Silver-halide materials. The market offers a very limited choice of commercial silver-halide recording materials for colour holography. In the past Agfa-Gevaert, Ilford and Kodak manufactured materials for monochrome hologram recording. None of these companies have holographic materials on the market now with the exception of *Harman Technology Ltd*[16] (former Ilford) which started a limited production of a new holographic emulsion however with a silver halide grain size not suitable for colour holography. In general, sensitivity of an emulsion depends on many factors, for example the laser wavelength, the exposure time (reciprocity failure), the development, (developer type, processing time, temperature, agitation, etc.) and storage conditions. Holographic sensitivity often varies from batch to batch, which is rare with conventional photographic materials. It is consequently recommended to make exposure and processing tests each time an important holographic recording is to be performed. It needs to be emphasized that for recording materials for colour holograms, high sensitivity is nice to have, but if it comes with an increased grain-size, it is not acceptable. Unfortunately it is much better to accept a longer exposure time (or to use a higher energy laser) to obtain a scatter-free recording.

In Russia today the manufacturing of holographic emulsions suitable for colour holography takes place in two companies, the *SLAVICH Joint Stock Company* [17] and *Sfera-S* [18] Both companies are located in Pereslavl, outside Moscow. Slavich manufactures different types of silver-halide materials for holographic purposes. Panchromatic materials for colour holograms are manufactured by Slavich under the name of PFG-03C. Sfera-S was formed by Yury Sazanov in 2004. Sazanov was earlier responsible for holographic plate manufacturing as director of the Micron plant at Slavich. In his new company, Sfera-S, located in an ex-Slavich building, he is now responsible for manufacturing a high-quality emulsion for colour holography which is available coated both onto glass plates as well as onto film. The main customer is *Geola uab*[19] in Vilnius, Lithuania where the film is used for their production of digitally printed colour holograms, marketed as *i-Lumograms*.[20] The Sfera-S emulsion [5] is currently the highest quality commercial panchromatic colour holography material available. It is sensitive to the short laser-pulse recording primarily used in the pulsed RGB digital holographic printers used by Geola. Both the Slavich and Sfera-S materials are available from Geola or from their international network of distributors.

Colour Holographic Ltd [21] is the primary UK manufacturer of ultra-fine-grain holographic emulsions. Their emulsion is based on the material that Birenheide manufactured in Germany. This type of emulsion (BB emulsion) was launched in 1996. Mike Medora of Colour Holographic acquired the rights to the BB products in 2001. Initially these emulsions were monochromatic and later a panchromatic emulsion was introduced, the BBVPan. Ulibarrena *et al*.[3,4] published reports concerning this new panchromatic ultra-fine-grain emulsion which has a mean grain size of 20 nm. The shrinkage or swelling of the emulsion after the plate is processed is one concern since the emulsion requires TEA pre-treatment to increase its sensitivity. In colour reflection holography a change in emulsion thickness is directly related to the wavelength of reconstruction and so affects the final replay spectrum and the colour reproduction of the image. Ulibarrena is now working at Colour Holographic and is responsible for emulsion manufacturing including the panchromatic emulsion which is now called RBG BBPAN. The company's production facility is based in Maldon, Essex, UK.

The other European manufacturer of colour emulsions *Ultimate – Holography* in France.[22] This emulsion is based on the work by the Gentet brothers.[2] Today Malasy Gentet (Yves Gentet's wife) produces and sells these products. 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. The company produces a panchromatic colour emulsion with a grain size of only 8 nm. However the production capacity of such plates is limited. Ultra-fine-grain monochromatic red and green sensitive emulsions are also manufactured. The Ultimate-08 plates are ready to use (no bath or adjustment needed before recording).

Some details about the Ultimate panchromatic material:

- Ultra-fine grain (8 nm), for unequalled resolution;
- Super high contrast material, with high diffraction efficiency holograms even at high Reference/Object ratio (1/10);
- Materials sensitive to all visible wavelengths;
- Recording of transmission or reflection holograms;
- Best diffraction efficiency on the market (up to 95%);
- Best sensitivity/resolution on the market;
- Substrates available: glass 3 mm thick or triacetate film of 190 µm;
- Storage recommendation at 4°C - lifetime more than 2 years; more than 6 months at room temperature.

At the time of writing it seems that *Colour Holographic* could not guarantee commercial supply of panchromatic silver-halide holographic plates to all customers. *Ultimate Holography* which, in the beginning, did not offer its panchromatic emulsion on the market but is now able to provide colour holographers with its excellent product. Commercial silver-halide holographic recording materials for colour holograms are listed in **Table 2**.

Table 2: Commercial silver-halide holographic recording materials for colour holograms

Material	**Spectral sensitivity** [nm]	**Resolving power** [line pairs/mm]	**Grain size** [nm]	**Substrate**
Colour Holographic				
RGB: BB-PAN	440-650	4000	20-25	Glass
Slavich				
Pan: PFG-03C	450-700	5000	10	Glass/Film
Sfera-S				
Pan: PFG-03CN	457-633	6000	9	Glass/Film
Ultimate				
Pan: 08-COLOR	460-650	10000	8	Glass/Film

2.1.2. 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*. [23] has been the main manufacturer of commercial photopolymer materials and has for a long time marketed these under the name of OmniDex.® The DuPont material requires only a dry processing technique (exposure to UV light and a heat treatment) to obtain a hologram. Since 1995 DuPont has manufactured a panchromatic material for colour holograms. [24,25]

Since early 2000 *DAI Nippon Printing Co., Ltd*. (DNP) [26] used the DuPont panchromatic material for producing photopolymer colour holograms. [27,28] Today DAI Nippon has access to a domestic (Nippon Paint) photopolymer product which is used exclusively for the in-house security colour hologram production.

A new German photopolymer material was introduced in 2011. The Bayfol®HX [29-31] by *Bayer MaterialScience AG* [32] intended for colour 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). It comes in rolls of up to 1.2 m wide. Besides creating fascinating optical effects this material can also be used to make ID cards and other documents which are forgery-proof. The current holographic performance of the material is as follows:

- Refractive index modulation $\Delta n = 0.03$ in reflection holograms;
- Diffraction efficiency = 98%;
- Colour sensitivity (450 - 650 nm);
- Suitable for both reflection and transmission holograms;
- Sensitivity for reflection holograms 100 $\mu W/cm^2$ - 50 mW/cm^2;
- 10-25 µm photopolymer thickness;
- Substrates PET or PC in roll format;
- Environmentally stable (UV, heat, humidity).

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 3-D 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. A few selected customers, for example *Zebra Imaging Inc.*[33] employing it for its large digital holograms are able to order the DuPont polymer materials.

Although today's panchromatic photopolymer materials constitute an extremely interesting solution for colour display holography, from a purely practical point of view, there therefore remains a sizeable question mark over whether these materials will be commercially applicable to display holography applications in the near-term.

3. Recording of colour holograms

Most colour holograms today are recorded using three laser wavelengths. Analogue reflection holograms of stable objects can be recorded using cw lasers. Panchromatic silver-halide emulsions or photopolymer materials are used.

3.1. Setup for recording colour holograms

A typical laboratory Denisyuk recording setup for analogue reflection three-laser colour holograms is illustrated in figure 1. The three laser beams are combined using two dichroic mirrors and pass through the same beam expander and spatial filter. The resulting "white" laser beam illuminates both the holographic plate and the object itself through the plate. Often the following three primary laser wavelengths are employed: 476 nm provided by an argon ion laser; 532 nm provided by a CW frequency-doubled Nd:YAG laser; and 647 nm provided by a krypton ion laser. It is possible to control independently the RGB ratio by individually changing the output power of the lasers, while the overall exposure energy is controlled solely by the exposure time.

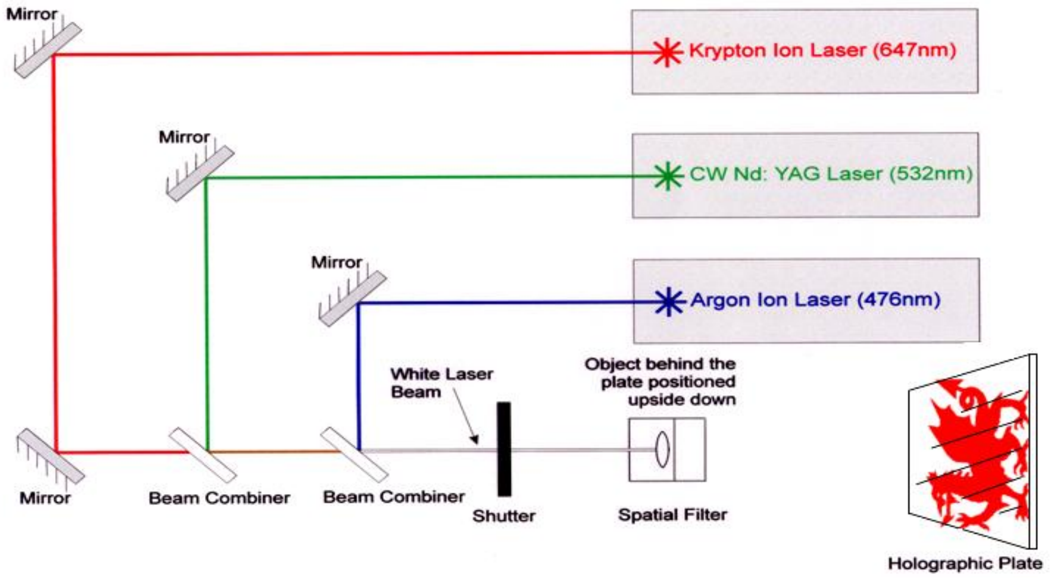

Figure 1. Setup for recording analogue colour reflection holograms

For most display purposes, the very large field of view obtainable in the Denisyuk hologram is very attractive. There are only very few colour hologram recording facilities in the world. For example, the problem with having to bring the objects and artefacts to a recording laboratory limits to wide-spread use of display holography in museums. Therefore there is a need to develop mobile colour holography recording equipment.

3.2 Mobile recording equipment

Gentet and Shevtsov [34] reported that they had fabricated a camera for recording colour holograms on 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 a green (λ = 532 nm) and blue (λ = 473 nm) solid-state lasers.

In 2011 the *Hellenic Institute of Holography* in Greece built a small portable three-colour analogue holographic camera, the Z3 RGB Holography YSB1 prototype camera to be used to record holograms of museum artefacts. The camera, depicted in figure 2, 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 at appropriate energy levels. The device consists of a main camera unit (MCU) built on top of a lightweight aluminium honeycomb and a control electronics unit (CEU). The three lasers are:

- Red laser: 638 nm at output power 80 mW (*CrystaLaser* laser);
- Green laser: 532 nm at output power 100 mW (*Cobolt Samba* laser);
- Blue laser: 457 nm at output power 50 mW (*Colbolt Twist* laser).

The lasers produce TEM_{00} emissions with coherence lengths of more than five meters each and the MCU contains suitable optics to generate a clean colinear mixed RGB beam. The Z3 has been successfully tested under wide ambient temperature and humidity ranges. The Z3 camera is accompanied by auxiliary equipment for beam orientation and a flexible vibration-absorbent setup for the object positioning. One example of a hologram recorded with the camera is shown in figure 3. The Hellenic Institute of Holography has also produced a portable darkroom for on-site processing (figure 4). At this conference Sarakinos *et al.*[35] report on this system and Jith[36] describes another mobile colour hologram camera.

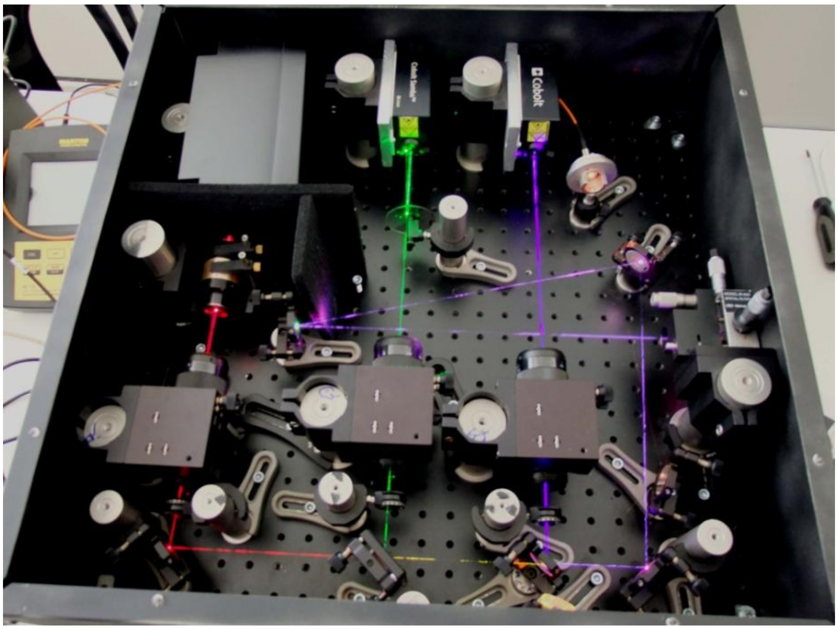

Figure 2. The Z3 RGB Holography YSB1 prototype mobile camera

Figure 3. Test colour hologram recorded with the mobile camera

Figure 4. Sarakinos and Lembesis in front of the darkroom tent

4. Lights for illumination display holograms

The light source to display the recorded holograms is also very important. In regard to colour holograms, the selection of a spotlight is actually more critical than for monochrome holograms. The colour temperature of the source has an influence on the colour rendering of the holographic image. The source size determines the image resolution in the parts of the image which appears in front of or behind the holographic plate. Arranging the correct illuminating angle (i.e. the same reference angle as was used for recording the hologram) between the holographic plate and the spotlight determines the correct colour of the displayed image. The distance from the source should be the same as the one used for the recording of the hologram to avoid any image aberrations.

The rapid progress in solid-state LED lighting has opened up new possibilities to illuminate colour 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 (20,000 to 100,000+ hours);
- 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;
- digital dynamic colour control – white point tunable;
- relatively low cost.

4.1 Preferred LEDs for colour holography

An alternative white LED technology to the most common phosphor-pumped LEDs is offered by RGB or RGBA LEDs. These combine red, green, and blue or red, green, blue, and amber chips onto one discrete package allowing the generation of white light or any of 256 colours by utilizing circuitry which drives the three diodes independently. In applications requiring a full spectrum of colours from a single point source, this type of RGB diode format is the preferred technique and more suitable for illuminating colour holograms. Currently one of the best methods for the generation of white light is the "RGB LEDs Combined" technology - i.e. the generation of white light using a combination of red, green and blue. Note however that his form of white light relies on the electrical control of three LED chips. Typical FWHM spectral widths are 24-27 nm.

When monochrome colour LED lights were first marketed in 2003, the *OptiLED* chip - a commercial LED spotlamp was introduced to illuminate monochrome reflection holograms. The 4° red, (627 nm, spectral width 20 nm), green (530 nm, spectral width 35nm) and amber (590 nm, spectral width 14 nm) versions provided suitable illumination for such holograms. The 2.5W LED spotlights had electric circuits allowing them to be operated at 90V to 240VAC. The monochrome LED lights were promoted and distributed by *Laser Reflections*.[37]

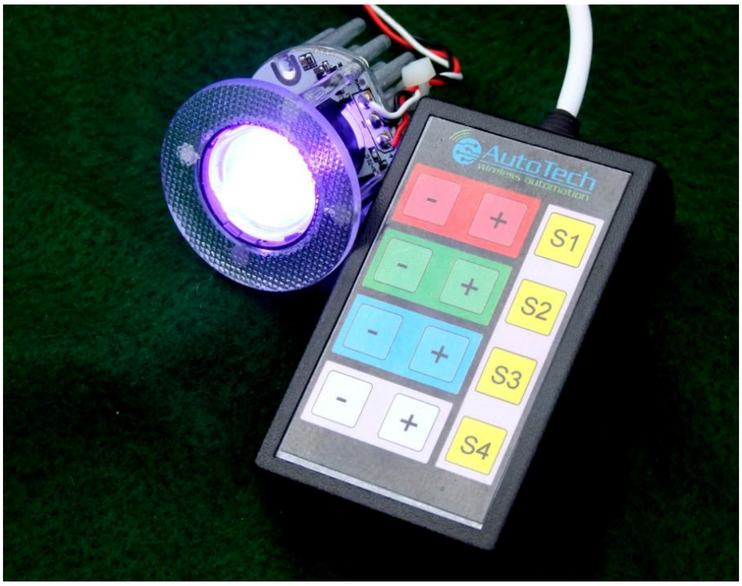

Figure 5. The *HoLoFoS* LED spotlight

4.2 Special LED spotlights for colour holograms

The *Hellenic Institute of Holography* has developed a special LED spotlight to illuminate colour holograms. The *HoLoFoS* LED spotlight, based on Cree LEDs, is manufactured at *AutoTech* [38] and is commercialised by *TAURUS SecureSolutions Ltd*.[39] 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 colour holograms. 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. The LED spotlight with its control unit is shown in figure 5.

The optics incorporated in the unit provide for an axial mixing of the LED beams resulting in a homogeneous colour 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 colour holograms which will be recorded with four or five laser wavelengths to obtain more or less perfect colour rendering. The current prototype unit uses three LEDs with the following spectral characteristics for the red, green and blue LEDs which correspond to the lasers of the *Z3 Holographic Camera* (mentioned in Section 3.2) The dominant wavelengths for the LEDs are:

- Red 620-630 nm;
- Green 520-535 nm;
- Blue 450-465 nm.

To demonstrate the advantage of using this LED light for displaying colour holograms, the same hologram was illuminated with a conventional halogen spotlight (figure 6) and the new *HoLoFoS* LED light (figure 7). The hologram in figure 6 was recorded on a slightly noisy Slavich emulsion to demonstrate the advantage of LED illumination. Note the increased contrast and sharpness obtainable with the LED light. This is also a good illustration of the vital importance of the illumination source in holography.

Figure 6. Halogen spotlight illumination

Figure 7. LED spotlight illumination

5. Colour holography around the world

There are very few companies or institutions that are able to record and produce analogue or digital colour holograms today. The main reasons are the costs, the expensive recording setup, and the demand on the recording material. Currently, the main producers are:

- Colour Holographic Ltd., England, UK;
- DAI Nippon, Japan;
- Geola Digital uab, Lithuania;
- Hellenic Institute of Holography, Greece;
- Holorad LLC, Utah, USA;
- Liti Holographics, Virginia, USA;
- Strasbourg University, France;
- Ultimate Holography - 3D Holoprint, France;
- Zebra Imaging Inc., Texas, USA.

It should be mentioned that RabbitHoles Media Inc. (former XYZ Imaging Co.) in Canada has ceased operation. The company produced art and promotional digital colour holograms, in particular for the movie industry, of which the 2010 *Avatar* hologram is an example. Some companies/universities are using the printing service provided by Geola Digital in Lithuania for printing the digital holograms marketed as *i-Lumograms*. They often have a digital camera system which can move along a horizontal rail to record people and any indoor or outside scenes and objects. Sometimes digital holograms are made from computer-generated images for which the institutions provide the 3-D data.

- 4-D Studio R, Dubai, United Arab Emirates;
- De Montfort University, England, UK;
- Forth Dimension, Indiana, USA;
- Holoxica Ltd., Scotland, UK;
- Tutto-Tondo Srl, Italy.

A recent example of a *Holoxica* hologram with Geola was to reveal the concealed detail of an Egyptian mummy unseen for more than two millennia. Thanks to the digital hologram imaging process the *Rhind Mummy* of the National Museum of Scotland's collection, has been revealed in true 3-D. A series of CT scans at Edinburgh Royal Infirmary carried out by the University of Edinburgh's Clinical Research Imaging Centre (CRIC) were used to create the hologram.[40] The Geola printing service is also used by artists, such as the Australian artist Paula Dawson who has created large-format digital holograms.[41] Martin Richardson in UK is frequently using the Geola printing service for his art holograms.

6. Applications of analogue colour holographic imaging

The most obvious applications of colour holography are for archival and exhibition purposes of rare and highly-valuable artefacts. Colour holograms of the analogue or digital type are also used in advertising and product promotions. Provided that the illumination of the colour holograms at exhibitions can be correctly arranged this application of display holograms may take off in the near future. In this section we focus on current applications of the technologies of full-colour analogue hologram recording and digital holographic printing.

6.1 Holographic copies of museum artefacts

Holography now offers the possibility to essentially duplicate artefacts - 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 artefact, 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.

It should be mentioned that digital holographic printing can also be usefully applied to museum recordings. By using a two-dimensional tracking camera system, high resolution digital image data from a museum exhibit can be recorded from over many different angles. This data may then be written onto a very high resolution digital hologram producing a digital holographic copy. 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 μm), 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. For instance, new holograms can be generated from the digital data whenever required. This means that as long as the original data is stored securely, there are no image life-time problems. In addition the same image data can be used to produce holograms of small and very large size. So museum exhibits can be exhibited in any format. Finally, such digital images are not constrained to be behind a glass plate.

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 artefacts is both hazardous and expensive. Transporting holographic copies on the other hand is not.

A final reason why ultra-realistic full-colour holograms are useful to museums is related to insurance costs of 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?

6.1.1 Museum holography in UK. In 2010 the *Colour Holographic Ltd* [21] in London started to record colour holograms in their own ultra-fine-grain panchromatic material. An example of a 20 cm by 25 cm colour museum hologram is shown in figure 8. It displays the front and back of a statuette. The 15 cm blue statuette is an 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.

A new product which the company has introduced is a nice wooden box for the display of colour holograms with an integrated LED light source built into the lid. When the box is opened, correct illumination of the hologram is provided. It is possible to switch holograms and the company offers the box with different holograms for sale. The box and a colour hologram are shown in figures 9 and 10.

Figure 8. Front and back recordings of an Ushabti Figure from private collection, recorded by *Colour Holographic Ltd* in UK

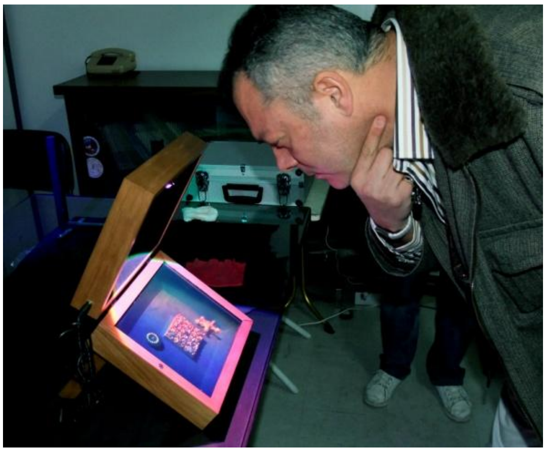

Figure 9. *Colour Holographic* display box

Figure 10. *Colour Holographic* hologram

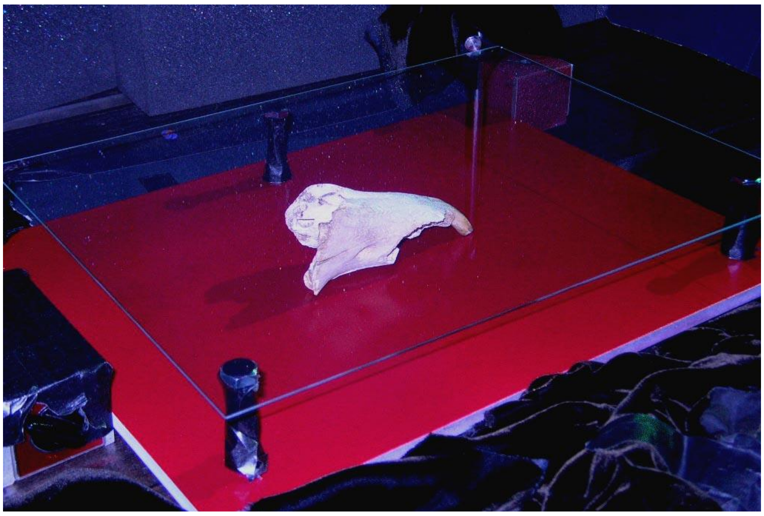

Figure 11. Horse jaw illuminated with "white" (RGB) laser light positioned under the holographic glass plate

Figure 12. Horse jaw hologram [British Museum 1959, 1203.1]

6.1.2 Virtual museum exhibition. One interesting colour hologram project[42] which was carried out in the Centre for Modern Optics' (CMO) laboratory by the present author in North Wales. The project was funded by the Esmee Fairburn Foundation entitled 'Bringing the Artefacts Back to the People'. The project involved collaboration with a number of major museums including the National Museum of Wales, the British Museum, the Maritime Museum in Liverpool, as well as with the Royal Commission for Ancient and Historical Monuments in Wales. David Crane of Llangollen Museum was responsible for the holography museum project and for arranging the touring exhibition. Colour holograms of various artefacts were recorded using the Denisyuk analogue techniques described in Section 3.1. Each artefact was positioned on a horizontal aluminium plate placed on the recording table. The recording holographic plate was positioned above and very close to the object. During the exposure, the divergent 'white' RGB laser light illuminated the object through the holographic plate at about a 45-degree angle from above. Several original holograms were recorded of each artefact to assure that a perfect hologram could be selected for the exhibition. After processing the exposed hologram plate it was sealed to a black glass plate using an index matching optical cement. The holograms were completed by the end of 2009, after which they were displayed as a travelling exhibition which toured North Wales and its borders. The exhibition first opened at Llangollen Museum in June 2010 and later at the museums of Grosvenor (Chester), Wrexham, Llandudno, Bangor and many others.

One of the recorded artefacts, supplied by the British Museum, was a 14,000-year-old decorated horse jaw bone (British Museum 1959, 1203.1) from the ice age, or late glacial period.[43] The jaw bone was positioned on a red-painted aluminium plate placed on the recording table. The recording setup is shown in figure 11 and the recorded colour hologram in figure 12.

Other recorded artefacts were the *Tudor Owl Jug* and *Sergeant at Arms Ring.* The hologram of the two objects is shown in figure 13. The artefacts were from the Grosvenor Museum in Chester, UK. In total, ten 30 cm by 40 cm colour holograms of different artefacts were included in the touring museum exhibition. The first place where the exhibition appeared was at the upper floor of *Llangollen Museum* in Wales, as shown in figure 14.

Figure 13. *Tudor Owl Jug* and *Sergeant at Arms Ring* hologram [Grosvenor Museum (Chester)]

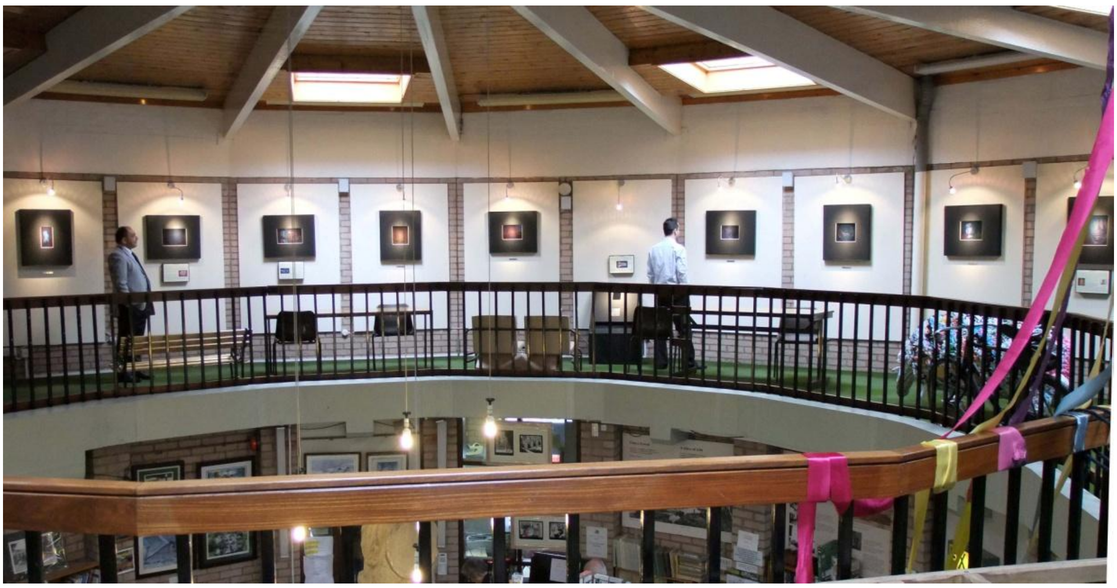

Figure 14. The travelling colour hologram exhibition at Llangollen Museum in Wales

Figure 15. Hologram of a Ceramic Vase recorded by *Yves Gentet*, *Ultimate,* in France

6.1.3 Museum holography in Greece. The *Hellenic Institute of Holography* in Athens has invested in colour recording equipment and is currently promoting colour holography. The primary goal of the Institute is to record Greek cultural artefacts through the "*HoloCultura*: *Applied Holography in Cultural Heritage*" project. The project consists of three parts:

- *Phase A*: Study necessary for implementation of the colour holography programme;
- *Phase B*: Recording of experimental colour holograms;
- *Phase C*: Pilot project involving the recording of cultural artefacts.

The Institute is active in a country with a unique cultural tradition of worldwide influence extending from classical ancient Greece to orthodox Byzantium Christianity. The use of display holography in the preservation, recording and public visual dissemination of artefacts from this cultural heritage is at the core of the activities of the Hellenic Institute of Holography. In addition to the possibility to record their own holograms, the Institute has produced museum holograms in collaboration with Yves Gentet in France (see figure 15, showing a hologram of a ceramic vase) as well as in cooperation with *Colour Holographic Ltd* in UK (see figure 8). More information about the holography institute in Greece is provided by Sarakinos *et al.* at this conference.[35]

6.2. Medical and scientific applications of colour holograms
An application of small analogue colour holograms used in endoscopy is reported at this conference by Osanlou *et al.*[44]

There are several scientific and medical applications of digital colour holograms. Educational 3-D images are used in biochemistry, medicine and life sciences showing images of protein structures, DNA and cells, for example. *Holorad Inc*.[45] in Utah, USA, has been in the field of medical holography during many years (operating as *Voxel Inc*.[46] providing full-parallax 3-D holograms of MRI and CAT data). The new company is producing scientific and advertising holograms including colour holograms. Hart *et al*.[47] is reporting on a large hologram at his conference.

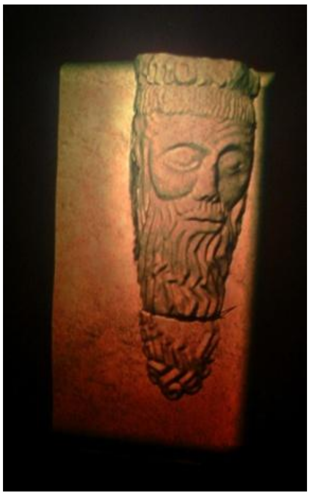

Figure 16. *Morus Head* digital hologram

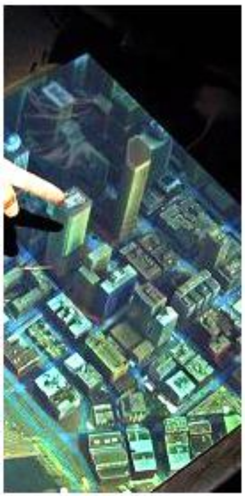

Figure 17. *Zebra* holographic map

7. Computer-generated colour holograms

Today it is not possible to obtain a computer-generated hologram (CGH) with the same huge information content as the laser-recorded analog ones of real objects. What may become possible in the future is a technique to compute and record the interference pattern that is stored in a reflection colour hologram which upon illumination can produce an image like the laser-recorded ones of real objects. The best compromise today is to use *holographic stereograms* which can provide high-quality CGHs. A holographic stereogram can be created by using a series of 2-D photographic images or 2-D images displayed on a LCD screen from which the hologram is recorded. In order to obtain a high-quality holographic image with a large field of view, many 2-D images are needed. It is also possible to use a laser scanner to obtain 3-D information about the object to create a digital hologram. An example of such a digitally-printed hologram by Geola Digital is the *Morus Head,* shown in figure 16. The *Morus Head* was found at the site of the Valle Crucis Abbey in Llangollen, Wales, and is now at National Museum of Wales in Cardiff.

For a long time *Zebra Imaging Inc*.[33] in Texas has produced large colour reflection holograms.[48] These holograms can be produced having both vertical and horizontal parallax with a 100^{o} field of view. The holograms are recorded on DuPont panchromatic photopolymer film. The main work is for military applications to produce holographic maps used both in headquarters as well as in the field. More information about Zebra and its projects are provided by Klug at this conference.[49]

8. Art colour holograms

Over many years *pseudo-colour holograms* of both the transmission and reflection types have been attractive to artists and there are many examples of beautiful holograms recorded by artists such as Inaki Beguiristain, John Kaufman and Rudie Berkhout. These holograms have been created by emulsion thickness manipulation or, in regard to rainbow holograms, the recording geometry. An example of an analogue Denisyuk reflection colour hologram by an artist is the *Stars and Stripes Flag* hologram (figure 17). Anaït Stephens who created this hologram in 1995 together with the present author used a pseudoscopic cast of the flag to make the image appear in front of the plate in the finished Denisyuk hologram. The digital printed colour holograms on ultra-fine-grain panchromatic emulsions have opened new possibilities of producing creative art holograms. Artists have been attracted to the new digital hologram medium. Paula Dawson[41] in Australia, who has always been interested in large-format holograms, has recently created several large digital colour holograms, printed by Geola. The 2007 *Luminous Presence*, a 0.95 m by 1.5 m hologram is shown in figure 18.

Figure 17. *The Flag* hologram by Anaït **Figure 18**. *Luminous Presence* by Paula Dawson

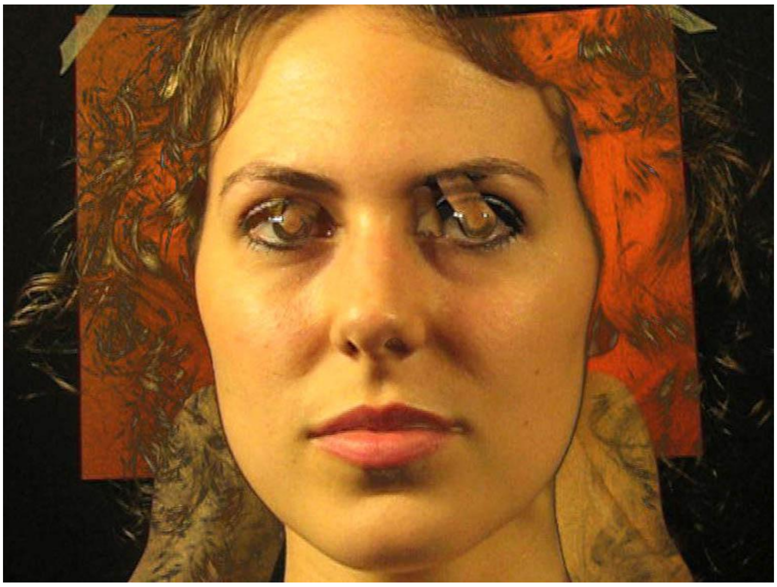

Figure 19. *Psychedelic Amy,* by Martin Richardson, UK

The combination of a photographically recorded 3-D portrait and added computer-generated content is the recent art hologram, *Psychedelic Amy*, size 50 cm by 60 cm, a digital hologram by Martin Richardson (De Montfort University, UK). This 2009 hologram, shown in figure 19, is another example of the collaboration with Geola being responsible for the printing. At first sight, this is a digitally retouched portrait of a young woman, but a ghost-like image can be seen to reflect in the subjects eyes as one moves from left to right, giving the impression of sixties-like psychedelic imagery. Several artists, for example Maria Isabel Azevedo and Sandra Oliveira (in cooperation with Martin Richardson) have started to work with this new and exciting medium.

The digital colour holograms may also become more popular among advertising companies. Currently the limited printing capacity makes it difficult to see a rapid market growth in this field. For both types of colour holograms a copying technique needs to be developed including required hardware. The new Bayer photopolymer would be suitable for commercial mass production of colour holograms provided it will be supplied to display holography companies in the future. Geola has started tests of contact-copying holograms on Bayer photopolymer materials. An example of a copied test hologram is shown in figure 20.

Figure 20. Photopolymer copy test hologram by *Geola*

8. The future of colour holography

The recording of large-format colour reflection holograms in ultra-fine-grain silver-halide and photopolymer materials is going to become more common, in particular for museums and documentation. With an optimal choice of the recording laser wavelengths within the visible spectrum, good colour rendering can be achieved in high-quality analogue colour holograms. The virtual colour image behind a Denisyuk holographic plate represents the most realistic-looking 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 an image of it. The wavefront reconstruction process recreates accurately the laser wavelengths scattered off the object during the recording of the colour hologram.

The large-format digital colour holograms may find increased applications in art and advertising where their possibility to include motion (caused by the viewer moving or by moving the light illuminating the hologram) is an attractive feature not possible in the Denisyuk holograms. New solutions for illuminating the recorded holograms will make it easier to use them in museums and for exhibitions. A new detailed book on ultra-realistic imaging based on analogue and digital colour holography will be published later in 2012 by the present author together with David Brotherton-Ratcliffe.[50]

References

[1] Bjelkhagen H I 1993 *Silver halide recording materials for holography and their processing*, Springer Series in Optical Sciences, vol 66 (Heidelberg, New York: Springer)

[2] Gentet Y and Gentet P 2000 "Ultimate" emulsion and its applications: a laboratory-made silver halide emulsion of optimized quality for monochromatic pulsed and full color holography, in *Proc. SPIE: HOLOGRAPHY 2000* vol 4149 ed T H Jeong and W K Sobotka pp 56-62

[3] Ulibarrena M 2004 A new panchromatic silver halide emulsion for recording color holograms, *Holographer.org* , 1-12

[4] Ulibarrena M, Vale M and Medora M 2006 Colourholographic Ltd BBPan panchromatic emulsions for recording colour holograms, in *Advances in Display Holography, Proc. 7th Int. Symposium on Display Holography* ed H I Bjelkhagen (London: River Valley Press) pp 73-77

[5] Sazanov Y, Gradova O, Zacharovas S, Bakanas R and Gudaitis G 2006 New ultra-fine grain photofilm for pulsed colour holography, in *Advances in Display Holography, Proc. 7th Int. Symposium on Display Holography* ed H I Bjelkhagen (London: River Valley Press) pp 65-68

[6] Bjelkhagen H I, Crosby P G, Green D P M, Mirlis E and Phillips N J 2008 Fabrication of ultra-fine-grain silver halide recording material for color holography, in *Proc SPIE: Practical Holography XXII: Materials and Applications* vol 6912 ed H I Bjelkhagen and R K Kostuk pp 09-1 - 14

[7] Bjelkhagen H I and Vukičević D 1995 Lippmann color holography in a single-layer silver-halide emulsion, in *Proc. SPIE: 5th Int. Symposium on Display Holography* vol 2333 ed T H Jeong pp 34-48

[8] Bjelkhagen H I, Jeong T H and Vukičević D 1996 Color reflection holograms recorded in a ultrahigh-resolution single-layer silver halide emulsion *J. Imaging Sci. Technol.* **40** 134-146

[9] Bjelkhagen H I and Mirlis E 2006 Colour holography – state of the art, in *Advances in Display Holography Proc. 7th Int. Symposium on Display Holography* ed H I Bjelkhagen (River Valley Press) pp 193-199

[10] Bjelkhagen H I and Mirlis E 2008 Color holography to produce highly realistic three-dimensional images *Appl. Opt.* **47** A123-A133

[11] Bjelkhagen H I 2009 Denisyuk color holography for display, documentation and measurement, *J. Holography Speckle* **5** 33-41

[12] Bjelkhagen H I 2011 Progress in colour holography and new recording materials, in *Holography – Culture, Art, and Information Technology*, *Proc. 8th Int. Symposium on Display Holography* (Shenzhen, China, Waterlands Resort, 13 – 17 July 2009) ed T H Jeong *et al.* (Tsinghua Univ. Press) pp 346-357

[13] Peercy M S and Hesselink L 1994 Wavelength selection for true-color holography *Appl. Opt.* **33** 6811-6817

[14] Kubota T, Takabayashi E, Kashiwagi T, Watanabe M and Ueda K 2001 Color reflection holography using four recording wavelengths, in *Proc. SPIE: Practical Holography XV and Holographic Materials VII* vol 4296 ed S A Benton *et al.* pp 126-133

[15] Bazargan K 2012 What are the ideal wavelengths for full color holography? *ISDH2012* IOP Publishing

[16] Harman Technology Ltd UK; www.harmantechnology.com

[17] SLAVICH Joint Stock Company Russia; www.slavich.com

[18] Sphera–S Ltd, Russia; www.geola.com

[19] Geola Digital uab, Lithuania; www.geola.lt

[20] Geola i-Lumogram; www.i-lumogram.blogspot.co.uk

[21] Colourholographic Ltd UK; www.colourholographic.com

[22] Ultimate – Holography France; www.ultimate-holography.com

[23] DuPont Autentication, USA; www2.dupont.com/Authentication/en_US/

[24] Trout T J, Gambogi W J and Stevenson S H 1995 Photopolymer materials for color holography, in *Proc. SPIE:Applications of Optical Holography* vol 2577 ed T Honda pp 94-105

[25] Steijn K W 1996 Multicolor holographic recording in Dupont holographic recording film: determination of exposure conditions for color balance, in *Proc. SPIE: Holographic Materials II* vol 2688 ed T J Trout pp 123-134

[26] DAI Nippon Printing Co. Japan; www.dnp.co.jp/international/holo

[27] Watanabe M, Matsuyama T, Kodama D and Hotta T 1999 Mass-produced color graphic arts holograms, in *Proc. SPIE*: *Practical Holography XIII* vol 3637 ed S A Benton pp 204-212

[28] Kodama D, Watanabe M and Ueda K 2001 Mastering process for color graphic arts holograms, in *Proc. SPIE: Practical Holography XV and Holographic Materials VII* vol 4296 ed S A Benton *et al.* pp 196-205

[29] Bruder F-K, Deuber F, Fäcke T, Hagen R, Hönel D, Jurbergs D, Kogure M, Rölle T and Weiser M-S 2009 Full-color self-processing holographic photopolymers with high sensitivity in red – the first class of instant holographic photopolymers *J. Photopolym. Sci. Technol.* **22** 257-260

[30] Bruder F-K, Deuber F, Fäcke T, Hagen R, Hönel D, Jurbergs D, Kogure M, Rölle T and Weiser M-S 2010 Reaction-diffusion model applied to high resolution Bayfol®HX photopolymer, in *Proc. SPIE: Practical Holography XXIIV: Materials and Applications* vol 7919 pp 0I-1-15

[31] H. Berneth H, F.- K. Bruder F-K, T. Fäcke T, R. Hagen R, D. Hönel D, D. Jurbergs D, T. Rölle T and M.-S. Weiser M-S 2011 Holographic recording aspects of high-resolution Bayfol®HX photopolymer, in *Proc. SPIE: Practical Holography XXV: Materials and Applications* vol 7957 ed H I Bjelkhagen pp 0H-1-15

[32] Bayer MaterialScience AG, Germany; www.bayermaterialscience.com

[33] Zebra Imaging Inc. USA; www.zebraimaging.com

[34] Gentet Y and Shevtsov M K 2009 Mobile holographic camera for recording color holograms, *J. Opt. Technol*. **76** 399-401
[35] Sarakinos A, Lembessis and Zervos N 2012 A transportable system for the *in situ* recording of color Denisyuk holograms of Greek cultural heritage artifacts in silver halide panchromatic emulsions and an optimized illuminating device for the finished holograms *ISDH2012* IOP Publishing
[36] Jith A 2012 Holographic color camera for recording artifacts *ISDH2012* IOP Publishing
[37] Laser Reflections, USA; www.laserreflections.com
[38] AutoTech Wireless Automation, Greece; www.autotech.gr
[39] Taurus SecureSolutions Ltd. Greece; www.taurus.com.gr
[40] Hooper R 2012 Hello mummy *New Scientist* No.2806 (26 May) 24-25
[41] Dawson P 2010 *Virtual Encounters; Paula Dawson Holograms* (Sydney, Australia: Macquarie University and Newcastle Region Art Gallery)
[42] Bjelkhagen H I and Osanlou A 2011 Color holography for museums: bringing the artifacts back to the people, in *Proc. SPIE: Practical Holography XXV: Materials and Applications* vol 7957 ed H I Bjelkhagen pp 0B-1-7
[43] Bjelkhagen H I and Cook J 2010 Colour holography of the oldest known work of art from Wales *The British Museum Technical Research Bulletin* vol 4 ed D Saunders (London: Archetype Publications) pp 87-94
[44] Osanlou A, Bjelkhagen H, Mirlis E, Crosby P, Shore A, Henderson P and Napier P 2012 Optimized processes in full color holographic endoscopy *ISDH2012* IOP Publishing
[45] Holorad Inc. USA; www.holorad.com
[46] Voxel Inc. USA; www.voxel.com
[47] Hart S, Brockbrader B, Burman D, Molteni W, Padiyar D, Padiyar J, Parris W, Reetz D, Shara M and Stevens C 2012 A stellar hologram *ISDH2012* IOP Publishing
[48] Klug M A 2002 Display applications of large scale digital holography, in *Proc. SPIE: Holography: A Tribute to Yuri Denisyuk and Emmett Leith* vol 4737 ed H J Caulfield pp 142-149
[49] Klug M 2012 Holograms by/for the masses *ISDH2012* IOP Publishing
[50] Bjelkhagen H I and Brotherton-Ratcliffe D 2012 *Ultra-realistic imaging – advanced techniques in colour holography* (London, New York: CRC Press Taylor & Francis Group) (in the print)