Color Holography and its use in Display and Archiving Applications

H. I. Bjelkhagen, Centre for Modern Optics, NEWI/OpTIC, St Asaph Business Park, St Asaph LL17 0JD, Wales, UK
P. G. Crosby, Right Eye Pictures, 1 Alstead Avenue, Hale, Cheshire WA15 8BS, England. UK

Abstract

An overview of the color holographic recording technique is presented along with the equipment and materials required to record, replay and display a color hologram. Color holography is the most accurate imaging technology known to science. It is now possible to produce 3D holographic images for display that are almost indistinguishable from the original object or scene. The application of color holography to museum cataloging, documentation, display and archiving is dThat'siscussed. Color holography offers an alternative route for the display, dissemination, study and investigation of rare or fragile or culturally sensitive artifacts. It offers new possibilities for studying, cataloging, authenticating, the examination, investigation and security of many types of precious objects and artifacts large and small. It also offers a route to novel display techniques and enables artifacts too fragile for normal display to be shown. An advantage is that rare, precious or high value artifacts can be displayed without any concern about theft or damage thus reducing costs for insurance, shipping, etc. The use of scanned digital recording can be used for recording very large objects or the production of displays for exhibition promotion. Until recently display holography was usually associated with monochrome 3D imaging. After the appearance of color holography it has become possible to record holographic images of 2D objects, such as oil paintings. A holographic contact recording of a painting reproduces the painting with all its surface texture details preserved, such as brush strokes, the painter's signature, etc. Possessing an exact copy of the painting could be important for insurance and restoration purposes, in case of theft or damage. The paper also discusses the rendition of color in a hologram. The major advantages of holographic reproduction are discussed together with its limitations.

Introduction

After the invention of black-and-white photography in the 19th century, there was a lot of interest in finding ways of recording color photographs. The first such technique was Lippmann photography invented in 1891, which can record high-fidelity 2D color images. [1] Interferential color photography, as Lippmann photography is also referred to, shows similarities to holography. A paper on old and modern Lippmann photography has been published by Bjelkhagen. [2] The principle behind these techniques is based on recording an interference structure in an ultra-high resolution emulsion. The fundamental difference is that, in the Lippmann case, there is *no phase recording* involved; the recorded interference structure is a result of *phase-locking* the light by reflecting the light from the object back into the emulsion. In holography, the phase information is actually recorded, being encoded as an interference pattern created between the light reflected from the object and a coherent reference beam. The recording of monochromatic light in a Lippmann photograph is easy to understand, and it is very similar to the recording of a reflection hologram. A broadband polychromatic spectrum, such as a landscape image, is very different. In this case, the recorded interference structure in the emulsion is located only very close to the surface of the emulsion in contact with the reflecting mirror. A color reflection hologram, on the other hand, is a result of the three-color RGB (red, green, and blue) process involving three monochrome recordings superimposed in the same emulsion.

In 1964 Leith and Upatnieks [3] presented the possibility of recording transmission holograms of 3D objects using laser light. Such a hologram, illuminated with a laser, generates a very realistic-looking 3D image. In principle, when illuminated with the same laser wavelength as was used for the recording, it is not possible to see any difference between the holographic image recorded and the laser-illuminated object itself. At that time only one laser wavelength was used to record and display the hologram, thus the 3D image was only monochromatic.

In the early 1960's a different type of holography, reflection holography, was introduced by Denisyuk [4,5] in the former USSR. He was trying to create an image which would reproduce a full illusion of the reality of scenes recorded in them. What was needed was to record and reproduce the wave field of light scattered by an object. He came up with the idea, and proved the possibility, of recording a complex object wave by means of mixing it with a reference wave of a simple form. Denisyuk introduced the reference wave from the opposite direction of the object wave. This idea was very much based on the work by Lippmann who had demonstrated that a volume recording of a standing wave had the property to reproduce the spectral composition of the recorded light. Denisyuk realized that the complicated interference pattern recorded could not only store the spectral information but also the *phase* of the wave-fronts. It should be mentioned that Lippmann wanted to create photographs that could reproduce a full illusion of the scenes recorded on them. He predicted that the surface of such photographs should seem to an observer as a window into the space of objects, all in full color. However, Lippmann did not invent holography but instead another 3D technique, integral photography [6] which was not based on interference but on a microlens array.

Eventually Denisyuk invented what has become known now as single-beam reflection holography or simply Denisyuk holography. Sometimes his technique is also referred to as Lippmann holography. In order to record the fine interference structures Denisyuk had to make his own recording materials which were emulsions of the Lippmann type. [7] Denisyuk placed a much more severe demand on the recording material's resolving power than Leith and Upatnieks had when recording their first holograms. The technique of recording Denisyuk holograms, using three RGB laser wavelengths, provides extremely realistic-looking 3D images.

Currently there is an interest in high-fidelity imaging with perfect color rendition, which can accurately capture the three-dimensional shape of an object. As regards color rendition, Lippmann photography is the only imaging technique that can directly record the entire color spectrum of an object or a scene. Holography can record and store laser light scattered off an object. The scattered light can be reconstructed by illuminating the holographic plate with the reference light which creates a full-parallax 3D image, visible behind the plate. Color holography is the technique to obtain a color 3D image of an object where the color rendition is as close as possible to the color of the real object.

Denisyuk's technique is very suitable for recording color display holograms. Color reflection holography of this type presents no problems as regards the geometry of the recording setup, but the final result is highly dependent on the recording material used, the processing techniques applied and the lighting used for replay. Until panchromatic ultra-fine grain silver halide emulsions were introduced, it was not possible to record high quality color holograms in a single emulsion layer. When the Russian company Slavich [8] introduced such an emulsion in the early 1990s, color holograms of the Denisyuk type were able to be recorded as demonstrated by Bjelkhagen *et al.* [9]

Modern Color Display Holography

Modern display holography is the imaging technique, in which not only the light intensity distribution in the original scene is recorded, but also the phase relations among the parts of the recorded objects are captured. Recording holograms with only one laser wavelength creates monochrome 3D images. Monochrome holography for recording 3D images for museums and archival purposes has not been very well received, mainly due to the absence of accurate color reproduction of the recorded objects. To accurately record full color holograms there are three important issues to consider. The first one is how many and which laser wavelengths to employ. The second issue is what material to select for the recording of the hologram; a panchromatic low light-scattering material of ultrahigh resolution is now used for this task. The third issue is how to reconstruct the image recorded in the hologram, i.e., what type of light source to use to illuminate the holographic plate for display.

Today the Denisyuk color reflection hologram recording technique is most often used since ordinary white light sources can be used to illuminate the recorded holograms. Both ultrahigh resolution silver halide materials as well as panchromatic photopolymer materials can be used for recording color holograms.

Any serious application of holography for archival purposes require accurate color rendering. Therefore choosing the correct recording wavelengths and the exact laser wavelengths is the key issue here. So far most color holograms have been recorded using three primary (RGB) laser wavelengths, resulting in rather good color rendition. However, some colors are not identical with the original colors of the object.

The Selection of Laser Recording Wavelengths

As suggested by Leith and Upatnieks [1] and as a starting point, three RGB laser wavelengths can be employed for recording color holograms, this follows the tristimulus theory of color vision, which implies that any color can be matched as a linear superposition of three primaries. There have been theoretical investigations carried out which studied the minimum number of laser wavelengths needed to give an error in color rendition that is small enough to be undetectable by an observer. In a recent publication by Bjelkhagen and Mirlis [10] this issue has been investigated. Using three laser wavelengths gives good color reproduction but greater accuracy can be achieved by using four to five wavelengths, above this number further improvement in color rendition is minimal. The result of a computer simulation is shown in Figure 1. In Table 1 the average color rendering error for three to seven optimal laser wavelengths is listed. The Macbeth ColorChecker target was used to illustrate the improved color rendering.

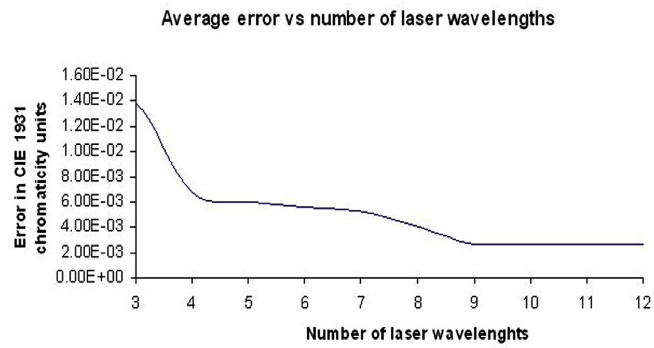

Figure 1. *Total average color error versus the number of wavelength sources that are used in the recording of the hologram*

Number of wavelengths	Optimal laser wavelengths (nm)	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

Table 1*. Total average error for three to seven optimal wavelengths*

Recording Materials

The choice of recording material is of equal importance to the choice of laser wavelengths for the recording of a color hologram. To be able to record high-quality color reflection holograms it is necessary to use extremely low light-scattering panchromatic recording materials. Currently the main materials in use are certain photopolymers and special emulsions based on silver halide. There are several problems associated with the recording of color reflection holograms. First, severe light scattering from the blue part of the spectrum excludes many materials from being used, e.g., many common holographic silver halide emulsions which in the past worked well for green and red monochrome holography. Second, multiple exposures in a single emulsion may reduce the diffraction efficiency of each individual recording. Third, the shrinkage of the material, that often takes place during or after processing, causes a wavelength shift in the reconstructed image.

Finally, white-light-illuminated reflection holograms normally show an increased bandwidth upon reconstruction, thus affecting the color rendition.

Photopolymer Materials

Certain panchromatic photopolymer materials are suitable for recording color holograms. Currently, the only commercial manufacturer of such a material is DuPont.[11,12] It has the advantages of easy handling and dry processing (only UV-curing and baking.) However DuPont announced recently that their materials will no longer be on the general market, with the exception of their in-house hologram production and a few selected customers such as those working in the field of optical document and product security. Photopolymer materials are in particular suitable for the mass-production of color hologram. Generally photopolymers have a lower sensitivity than silver halide materials.

Silver Halide Materials

Silver halide materials have been used in holography from the beginning. [13] These materials are the most sensitive ones among holographic recording materials and are used for large-format hologram. However, there are very few materials of the silver halide type on the market suitable for color holography. What is needed here is a special panchromatic ultra-fine grain silver halide emulsion (grain size about 10 nm or less). The only commercial producers of such materials are Russian companies: Slavich [8] and Sphere-S. [14]

To investigate and manufacture materials specially suited for color holography, the European “SilverCross Project” [15] was created. The chosen technical route for this project was to continue the use of materials based on photographic silver halide technology as over the years this has proved to produce the results of the highest recording quality and image fidelity. The outcome of the project resulted in an emulsion highly suitable for recording high-quality color holograms.

Setup for Recording Color Refection Holograms

To obtain realistic-looking holographic images the preferred type is the reflection hologram. So far we have only used a setup with three RGB laser wavelengths which is illustrated in Fig. 2. For most display purposes, the very large field of view obtainable in a single-beam Denisyuk hologram is very attractive (180-degree horizontal and 180-degree vertical). The different laser beams necessary for the exposure of the object pass through the same beam expander and spatial filter. The "white" laser beam illuminates both the holographic plate and the object itself through the plate. Each of the three primary laser wavelengths forms its individual interference pattern in the emulsion, all of which are recorded simultaneously during the exposure. In this way, three holographic images (a red, a green, and a blue image) are superimposed upon one another in the emulsion. Three primary laser wavelengths are employed for the recording: for example, 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. Two dichroic beam combiners are used for adding the three laser beams. By using such beam combiners, simultaneous exposure of the holographic plate can be performed. This makes it possible to control independently the RGB ratio and the overall exposure energy in the emulsion. The RGB ratio can be varied by individually changing the output power of the lasers, while the overall exposure energy is controlled solely by the exposure time.

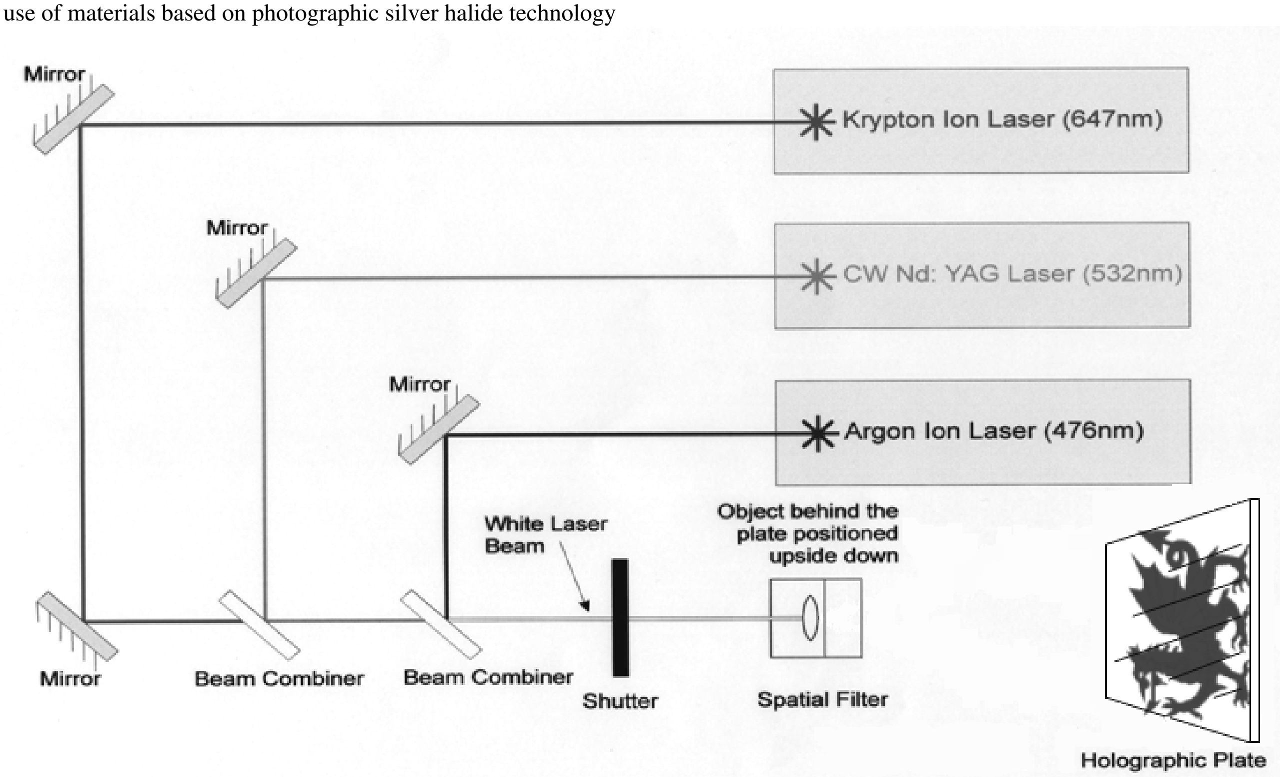

Figure 2. Setup for recording a Denisyuk color reflection hologram

Displaying Recorded Holograms

The most limiting factor in holography is the problem of displaying the holograms. The light source used to illuminate recorded holograms is very important. The selection of a suitable spotlight for color holograms is more critical than choosing one for monochrome holograms, as the color temperature of the source has an influence on the color rendering of the holographic image. In addition, the display source size determines the blur in the parts of the image which appear either in front of or behind the plane of the holographic plate. Arranging the correct illuminating angle, (i.e. the same reference angle that was used for recording the hologram), between the holographic plate and the spotlight ensures that the correct color of the displayed image is seen. To avoid any image aberrations, the distance from the display light source to the holographic plate, should be the same as the distance from the divergent point of the reference beam to the plate used during the recording. The color balance for the recording of a color hologram must be adjusted bearing in mind the type of spotlight that is going to be used for the display of the finished hologram. This is why holograms can only be considered in fixed installations, for example, using special track lighting with adjustable spotlights.

The rapid progress in solid-state lasers, LEDs and OLEDs has opened new possibilities for the display of color holograms. The ideal situation would be if the wavelengths of the LED/OLED light source could match the recording laser wavelengths used. This would guarantee that only the light from the source (mixture of the wavelengths) to illuminate the hologram is the same as the one used to create the holographic image. Using a halogen spotlight, which is the common practice today, a large part of the light spectrum emitted is illuminating the surface of the plate without having any impact on the intensity of the image. Instead it creates light scattering, lowering the image contrast. 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 for improved design and sharper holographic images,
- high durability and robustness to thermal and vibration shocks,
- low energy usage / high energy efficiency,
- no IR or UV in the beam output,
- directional light output for increased system efficiency,
- digital dynamic color control – white point tunable.

Holograms for Archival Purposes and Museum Work

As it is only recently that color holographic recording has become possible, the use of holography in museums has been very limited. Displaying artifacts recorded as monochrome 3D images has proved to be of little interest to museums, however there are some monochrome examples, of very rare objects, that have been shown. This happened in the early days of holography and in particular holograms were recorded for museums and exhibitions in the former USSR and East-European countries. The reason for this was the very high-quality recording materials that existed there. Even if the images were monochromatic, most visitors had never seen holograms and since the quality of the monochrome images were impressive, people really liked the holograms. About 1980 the Ukrainian Ministry of Culture together with the Ukrainian Institute of Physics started a new program. The purpose was to develop holographic laboratories in museums to be able to record holograms of unique artifacts. The program included the State Museum of History, the Herson State Historical Archeological Museum, Ukrainian Museum of Historical Treasures and other museums. Some of these holograms were brought to the West. For example, the 1985 exhibition "*Holography – Treasures of the USSR*" at the London Trocadero Centre displayed many holograms including artifacts from Ukraine, the Northern Black Sea area, Byzantine and Scythian works of art, and from the Hermitage. This exhibition was organized by the Academy of the Sciences of the USSR in cooperation with Light Fantastic Ltd. UNESCO published articles on the cultural heritage and holography in 1982 and 1984. [16,17]

After this very little happened with regard to holography being used for museums or archival purposes. The main reason was that museums were not that interested in using monochrome holograms. The lack of color was a real drawback to them and holography got more or less forgotten. That was the time when embossed holograms appeared on credit cards and now most people will think of such holograms when the word "hologram" is mentioned. However, work on improving display holography and developing color holography has been continuously going on. In Japan, Kubota and Nishimura [18,19] have advanced the technology and described the recording of cultural assets by color holography.

Over many years another holographic technique, hologram interferometry for nondestructive testing of art objects has been used. Amadesi *et al*. [20] described a holographic method for detecting separate regions between priming layers and the underlying wood support in an old fifteenth-century Italian painting *Santa Caterina* by Pier Francesco Fiorentino. The support panel of the painting is made of two slabs of poplar wood glued together. Double-exposed holograms of the painting were recorded, the painting having been previously slightly heated by a current of warm air. The two exposures were made with a five-minute interval between them. The separate regions were revealed in the fringe pattern of the recorded hologram. Later, in another publication by Amadesi *et al.* [21]sandwich holography fringe evaluating technique was employed. This technique makes it easier to detect detachments of adhesion in paintings. In this case another fifteenth-century painting of the Perugina School, *Madonna col Bambino*, was examined.

Reproduction of 3D artifacts

In this paper we focus on color holography for reproduction of artifacts. The new SilverCross emulsion was employed and the holograms were recorded with the RGB technique described above. It is important to point out that due to the ultra-fine grains of the recording material (8 – 15 nm), the holograms demonstrate very low light scattering in the blue region of the spectrum. An important aspect of the hologram is its ability to retain the spectral information of the image recorded. In order to retain this information the processed holographic emulsion must not introduce changes to the interference pattern recorded. If the emulsion shrinks or swells during the processing of the recorded hologram, it will distort the spectral information and it will introduce a color shift. The spectral stability of the hologram is mainly dependent on the material that is used during the recording. The SilverCross emulsion is designed to provide high spectral stability and thus minimal color distortion.

The ultra-fine grain panchromatic SilverCross emulsion is most suitable for this sort of application. Illustrated in Fig. 3 is a photograph of a color hologram of some prehistoric items that were found in central Europe. The sculptures are believed to be two thousand years old and they probably represent mammoth figures. The artifacts were provided on loan from "The Arthur Kendall Collection" from the "Department of Palaeontology" at "The Natural History Museum" in London. Figure 4 depicts a photograph of another hologram made on the SilverCross material; the image of the Franklin Mint decorative plate "*Princess of the Iris"* by M. Nolte.

Reproduction of 2D art such as oil paintings

Over the centuries, there has been a lot of interest in the preservation and reproduction of various valuable oil paintings. It was common in the past to have famous paintings reproduced by artists who made high-quality copies of them. One artist who made copies of ancient Egyptian art was Joseph Lindon Smith (1863-1950). His painting technique renders stone wall so realistically, complete with chips and cracks, that his paintings are often mistaken for the actual wall surface.

After the invention of photography and, especially of color photography, large numbers of paintings have been photographically reproduced. Such photographs are often used, for example, in art books, exhibition catalogs, museum postcards, posters, etc. An example of an early type of color photography is the Lippmann photograph by H. Lehmann who in 1907 made a reproduction of an oil painting, entitled *Wäscherinnen am Gardasee*, painted by E. Kulthan from Jena. Since Lippmann photography records the entire color spectrum of a given object, the color reproduction of the said painting was remarkably accurate. In addition to perfect color reproduction, a Lippmann photograph has very good archival stability, as no pigments or dyes are embedded in the emulsion - only an interference pattern is recorded in a black-and-white photographic emulsion. The image colors are reproduced by means of illuminating light reflected from and interacting with the recorded interference pattern in the emulsion.

More recently digital photography has been used to reproduce paintings for art exhibitions, where reproductions are intended to be used instead of the original paintings, as their substitutes. The Butler Museum of American Art in Youngstown, Ohio, made a digital reproduction of a fifty-million dollar oil painting *Snap the Whip* by Winslow Homer from 1872, when the original painting, which is otherwise on permanent display at the Butler Museum, was to participate in an exhibition at another museum. During that period of time the Butler Museum did not wish to display an empty space on the wall, and so a special type of digital reproduction called a *giclée* was made. A giclée is a high-resolution digital image printed with an inkjet printer onto an archival-quality canvas, using a special type of ink.

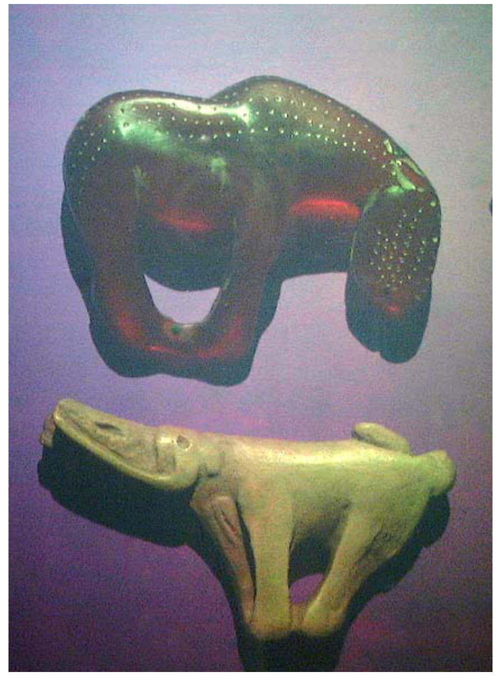

Figure 3. *Photo of a 20 x 30 cm hologram of artifact*

Figure. 4. Photo of a 30 x 40 cm hologram of from The Natural History Museum in London "Princess of the Iris" decorative plate

Remember that photographic reproductions of color holograms would be no different from photographs directly recorded of the objects. The quality of the color holograms can only be experienced by viewing the actual holograms.

Another place where high-quality reproductions of paintings are used is the Otsuka Museum of Art in Japan. [5] The coming into being of this museum, which opened in 1998, is owed to M. Otsuka who wanted to create a museum that could host the most famous paintings in the world under one roof. The museum has many reproductions of great paintings by Picasso, Goya, Rembrandt, van Gogh, Monet, and many other famous artists. The advantage is that paintings of the same artist, or with the same motif, located normally in different places, can now be seen at one and the same place now. For example, all six *High Altar* paintings by El Greco can now be admired at the Otsuka Museum, which is a special treat, since the original paintings are located in different parts of the world. All paintings at the museum are photographic reproductions which have been transferred onto ceramic tiles, using silkscreen printing techniques.

Color holography is the imaging technique which is best suited of all the techniques for the reproductions of paintings. In addition, color holograms, similarly to Lippmann photographs, have very high archival stability. To some people it may sound a bit odd to consider an imaging technique primarily associated with 3D imaging to be useful for recording of flat objects. We must remember that since true color holograms can now be recorded, holography is a serious candidate for this type of application. In the following we will give some examples of the advantages of using color holograms in the field of graphic arts reproduction. [23]

As an example, a *still life* oil painting, 20 cm by 25 cm, is shown in Figure 5. The painting, which is not an art piece or of any significant value, was selected mainly because it was painted on wood with a pronounced surface texture. During the recording, the emulsion of the holographic plate was facing the painting and it was brought in close contact with it. The reference beam was introduced at a more oblique angle than it is normally done when recording other color holograms since, in this case, there were no object shadows to consider. By using a steep reference angle it is easy to illuminate the final hologram at that angle with a spotlight located only a short distance away from the hologram plate. A color photograph of the recorded color hologram reproduction of the painting is shown in Figure 6.

The main idea behind this hologram was to introduce the concept of holographic reproductions of paintings. At this stage it may not be possible to record an absolutely perfect color reproduction with only three laser wavelengths. A detail of the painting texture, visible when observed at an angle, is shown in Fig. 7. The same surface texture from the hologram is also shown in Fig. 8, which illustrates the advantages of using holography. In this case, the hologram is illuminated from the side, not at the correct reconstruction angle, which means that the colors are not expected to be correct here. Nevertheless the holographic reproduction can be studied in more or less the same way as the real painting can be investigated. Another example is illustrated in Fig. 9, where the brush strokes in the hologram can be studied under high magnification.

Computer-Generated Holograms

So far we have described analog holograms of the Denisyuk type. These are the holograms that give the highest possible resolution and image quality. Such holograms are recorded in scale 1:1 (the objects are positioned behind the holographic plate during recording) In most cases this gives the perfect documentation since there is no doubt about the actual size of the artifact. However, for large objects, large holographic plates or film are required. Here we are limited to objects no larger than a square meter, since that is the size of the glass plates currently possible to obtain.

***Figure. 5**. Oil painting*

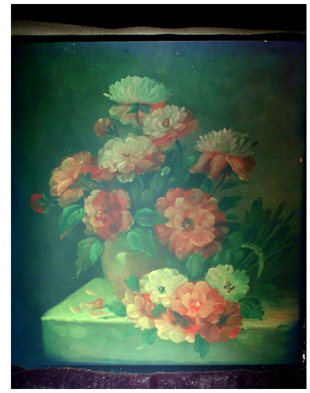

***Figure 6**. Hologram reproduction*

***Figure 7**. Detail, oil painting*

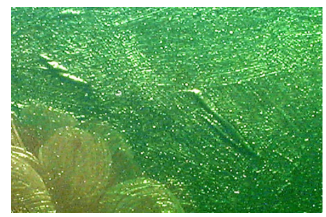

***Figure 8.** Detail, hologram reproduction*

***Figure 9.** Brush strokes, holographic reproduction*

For larger objects there is a possibility to use a digital camera to record large real scenes or objects. The camera produces a sequence of high-resolution digital photographic images in a format designed to be used with special holographic printer. Large-format color holograms (size up to 1.2 m by 2 m) can be printed on film. These holograms are printed pixel by pixel (size 0.8 mm by 0.8 mm). However, the image resolution depends on the pixel size and these holograms are only suitable for large objects, since the viewing distance is normally larger. The system consists of a digital holographic printer employing a pulsed RGB laser for producing large-format color reflection holograms from computer-generated images or digitally recorded real objects. [24]

Conclusions

The virtual color 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. By choosing the optimum recording laser wavelengths within the spectrum, good color rendering can be achieved. The wave-front reconstruction process recreates accurately the laser wavelengths scattered off the object during the recording of the hologram. This 3D imaging technique has many obvious applications, in particular, displaying unique, precious or expensive artifacts. The application of color holography to museum cataloging, documentation, display and archiving could become an important technique. It is suitable for the display of rare or fragile or culturally sensitive artifacts. It also offers a route to novel display techniques and enables artifacts too fragile for normal display to be shown. An advantage is that rare, precious or high value artifacts can be displayed without any concern about theft or damage thus reducing costs for insurance, shipping, etc. Denisyuk color holography may become an important reproduction technique for 2D objects as well, such as, e.g. oil paintings. Holograms will not fade or change color even if they are continuously on display. This fact is of importance from an archival point of view.

Acknowledgements

Financial support was provided through the SilverCross project EC FP6 CRAFT project 005901, carried out between 2004 and 2007.We would like to thank D. M. Green and E. Mirlis for extensive contribution to the silver halide emulsion project. Thanks are also due to N. Phillips acting as a consultant as well as the European SilverCross project partners. We also would like to acknowledge that M. Richardson assisted in recording the artifacts provided by R. Kruszynski at The Natural History Museum in London.

References

[1] G. Lippmann, "La photographie des couleurs," *C. R. Hebd. Séances Acad.* 112, pg. 274 (1891).
[2] H. I. Bjelkhagen, "Lippmann photography: reviving an early colour process," History of Photography 23 (3), pg.274 (1999).
[3] E. N. Leith and J. Upatnieks, "Wavefront reconstruction with diffused illumination and three-dimensional objects," J. Opt. Soc. Am**.** 54, pg. 1295 (1964).
[4] Yu. N. Denisyuk, Dokl. Akad. Nauk. (Academy of Sciences Reports, USSR) 144 (6), pg.1275 (1962) [Transl.: Photographic reconstruction of the optical properties of an object in its own scattered radiation field]. Sov. Phys. Doklady **7**, pg.543 (1962).
[5] Yu. N. Denisyuk, "On the reproduction of the optical properties of an object by the wave field of its scattered radiation," Opt. Spectrosc. (USSR) 14, pg.279 (1963).
[6] G. Lippmann, "Épreuves réversibles photographies intégrales," *C. R. Hebd. Séances Acad.* 146, pg.446 (1908).
[7] Yu. N. Denisyuk and I.R. Protas, "Improved Lippmann photographic plates for recording stationary light waves," Opt. Spectrosc. (USSR) 14, pg.381 (1963).
[8] SLAVICH Joint Stock Co., Micron Branch Co., 2 pl. Mendeleeva, 152140 Yaroslavsl Region, Pereslavsl-Zalessky, Russia.
[9] H. I. Bjelkhagen, T. H. Jeong, and D. Vukičević, "Color reflection holograms recorded in an ultrahigh-resolution single-layer silver halide emulsion," J. Imaging Sci. Technol. 40, pg.134 (1996).
[10] H. I. Bjelkhagen and E. Mirlis, "Color holography to produce highly realistic three-dimensional images," Appl. Opt. 47, pg.A123 (2008).
[11] W. J. Gambogi, W. K. Smothers, K. W. Steijn, S. H. Stevenson, and A. M. Weber, "Color holography using DuPont holographic recording film," in *Holographic Material.* Proc. SPIE 2405, pg.62 (1995).
[12] T. J. Trout, W. J. Gambogi, and S. H. Stevenson, "Photopolymer materials for color holography," in *Applications of Optical Holography.* Proc. SPIE 2577, pg.94 (1995).
[13] H.I. Bjelkhagen, Silver Halide Recording Materials for Holography and Their Processing, Springer Series in Optical Sciences, Vol. 66. (Springer-Verlag, Heidelberg, New York 1993)
[14] SPHERE-S Ltd. Magistralnaja Street 10A, 152023 Yaroslavsl Region, Pereslavsl-Zalessky, Russia.
[15] The SilverCross project, European EC FP6 CRAFT project 005901.
[16] I. G. Yavtushenko and V. B. Markov, "Holography" in *Museum* Vol. XXXIV, No. 3, (1982).
[17] V. B. Markov, G.I. Mironyuk, and I.G. Yavtushenko, "Holography and its applications in art work," UNESCO CLT/84/WS.16 (1984).
[18] T. Kubota and M. Nishimura, "Recording and demonstration of cultural assets by color holography (I) - Analysis for the optimum color reproduction," J. Soc. Photogr. Sci. Tech. Jpn. 53, pg.291 (1990).
[19] T. Kubota and M. Nishimura, "Recording and demonstration of cultural assets by color holography (II) - Recording method of hologram for optimizing the color reproduction," J. Soc. Photogr. Sci. Tech. Jpn. 53, pg.297 (1990).
[20] S. Amadesi, F. Gori, R. Grella, and G. Guattari, "Holographic methods for painting diagnostics," Appl. Opt. 13, pg.2009 (1974).
[21] S. Amadesi, A. D'Attorio, and D. Paoletti, "Sandwich holography for painting diagnostics," Appl. Opt. 21, pg.1889 (1982).
[22] Otsuka Museum of Art, 65-1 Tosadomariura Aza Fukuike, Naruto-Cho, Naruto, Tokushima Prefecture 772, Japan.
[23] H. I. Bjelkhagen and D. Vukičević, "Color holography: a new technique for reproduction of paintings," in *Practical Holography XVI and Holographic Materials VIII*. Proc. SPIE 4659, pg. 83 (2002).
[24] D. Brotherton-Ratcliffe, "Large format digital colour holograms produced using RGB pulsed laser technology,"in *Advances in Display Holography*. Proc. The 7th International Symposium on Display Holography, pg.200, River Valley Press (2006).