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Colour holography of the oldest known work of art from Wales

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Summary Dated as about 14000 years old, the jawbone of a horse decorated with zigzag patterns from Kendrick's Cave, near Llandudno in North Wales, is the oldest known work of art from Wales. While it was on loan to Llandudno Museum as part of the British Museum's UK Partnership Programme, the opportunity arose to reproduce it as a hologram using the most accurate currently available imaging technology. This contribution describes how the jaw fragment was reproduced using the latest techniques in three-dimensional colour holography, developed at the Centre for Modern Optics (OpTIC) at Glyndŵr University, St Asaph. The technique allows ultra-realistic colour images to be reproduced of the same size as the original. Using the horse jaw as a test case, the technique is described and the advantages of holographic reproduction, which include good three-dimensional image resolution, field of view and colour rendition, are outlined. Potential applications and limitations of the technique in archaeological research and museum outreach work are discussed.

INTRODUCTION

The Kendrick's Cave horse jawbone

In 1880 the lapidary Thomas Kendrick found a decorated chin fragment from a horse jawbone in a cave on Great Orme, Llandudno, Wales which was then named after him. The bone has a pattern of incised zig-zag lines on the underside and is the oldest work of art known from Wales. Dated to about 14000 years old it is one of only a small number of decorated Late Ice Age objects found in Britain. After Kendrick's death the object disappeared but came to light again in London in 1959 when a new owner brought it into the British Museum and it was identified as the missing piece from the cave. As there was no museum service in Llandudno at that time, the British Museum acquired the object and it has been on permanent display ever since (registration number 1959,1203.1: Figure 1).

Holograms

Holograms are images recorded by using laser light, which can be seen in three dimensions without special eyewear. While many will be familiar with embossed holograms as security devices on credit cards, this kind of mass application hardly does justice to the quality of three-dimensional imaging that can now be achieved with holography. This contribution describes how a new type of colour hologram is recorded and considers potential uses for displaying objects in museums. This application, which is termed display holography, is based on a technique originally introduced for monochrome holograms and now developed to record and display colour three-dimensional images of objects. Laser light illumination is used during the recording, while the subsequent display of the recorded hologram requires a special illumination technique that normally utilizes standard 'white light' sources. Its application as part of the *Bringing the Artefacts Back to the People* project, which was organized by David Crane of Llangollen Museum and funded by the Esmée Fairburn Foundation, shows how this pioneering technique can now be used to provide images that are so realistic that they can stand in place of the original objects in circumstances where the museum facilities are insufficient to allow the latter to be displayed.

HISTORICAL BACKGROUND

Early developments

Although the imaging technique known as holography was invented in 1948 by Dennis Gabor [1], it had no practical

FIGURE 1. The decorated chin fragment from a horse jawbone from Kendrick's Cave (BM 1959,1203.1)

applications until the early 1960s when lasers were developed. The use of laser light for recording holograms happened almost simultaneously in both the USA [2] and the former USSR [3]. Since that time, interest in holography has developed and given rise to many varied applications in science, industry, medicine and art, as well as banking security.

The theory of holography and its applications will not be detailed here as they are well described in the literature [4]. Basically, holography is an imaging technique using lasers that not only records the light intensity distribution in the original scene, but also captures the phase relations between the parts of the recorded objects, storing these as a complex interference pattern in the emulsion of the photographic recording material. The storage of this phase information is made possible by adding a uniform coherent reference beam to the laser light scattered by the object; during exposure the recording medium is thus simultaneously exposed to both reference and object-scattered radiation. To view the recorded hologram it is necessary to recreate the reference beam, which is used to illuminate the holographic plate. There are two main holographic techniques: transmission holography, in which the reference beam and object-scattered light reach the plate from the same side during the recording; and reflection holography, where the reference beam illuminates the recording plate from the opposite side from the object-scattered light. The advantages of reflection holography for museum displays are that the holograms are easier to record in colour and can be displayed using ordinary 'white light' sources.

In the early days of holography, holograms of various artefacts were recorded and introduced to museums as a new three-dimensional imaging technique. The main problem was that these holograms were recorded using only one laser (usually operating at wavelengths in the red or green region of the spectrum). These produced red or green monochrome holographic images that appeared spatially realistic, but with colour reproduction that was unacceptably poor for most potential museum applications.

In the early 1980s photographic companies in the former USSR and eastern European countries were able to manufacture high quality recording materials that were used to produce large-format monochrome holograms. These encouraged the Ukrainian Ministry of Culture together with the Ukrainian Institute of Physics to develop holographic laboratories in museums to record holograms of unique artefacts. The programme included the State Museum of History, the Herson State Historical Archaeological Museum, the 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* organized by the Academy of Sciences of the USSR in cooperation with Light Fantastic Ltd at the Trocadero Centre in London. Many holograms were on display, including recorded artefacts from the Ukraine, the northern Black Sea area, Byzantine and Scythian works of art, and objects from the State Hermitage Museum [5].

Following these developments UNESCO published articles on cultural heritage and holography, for example [6]. Although Markov, a co-author of the UNESCO report went on to describe early applications of holography in museums [7, 8], the technique was not widely adopted because of its expense and the need for special recording laboratories.

The Lindow Man hologram

One rare application from this period was the production of a monochrome hologram of Lindow Man made for the British Museum in 1987 by Richmond Holographic Studios using a pulsed ruby laser [9]. The Lindow remains (1984,1002.1) consist of the head and upper body of a man who died sometime in the first century AD. Preserved in the peat of a Cheshire bog, the body was an exceptional find in Britain and many new techniques were used in its documentation and analysis. As soft tissue rather than bone survived, the body has a flattened appearance and holography was applied to help the public appreciate the three-dimensional form of the body, which has to be displayed in low light conditions to ensure its long-term preservation. A press release from May 1987 describes how the hologram highlighted the features of the body "in quite extraordinary detail" and enabled visitors "to get much closer than is possible when viewing the body itself" [10]. The press release also makes it plain that the image was so clear that "every hair of his beard, moustache and eyebrows seems real and the ligature used to throttle him is very evident" [10]. Although it did not contribute to the scientific understanding of this highly publicized discovery, the Lindow Man hologram brought an additional, novel interest when first displayed. Subsequent changes to the gallery layout made it difficult to illuminate the hologram and, consequently, it is no longer on display.

COLOUR HOLOGRAPHY

Since the early trials described above, display holography has been developed so that it is now possible to record full colour holograms. At the time of writing, colour holography is the most accurate imaging technology capable of producing three-dimensional images for display and these are almost indistinguishable from the original objects. Holograms recorded on special photographic plates provide a form of reproduction that is more accurate than photography or computer imaging and also arouse public interest in a quite different way from a technical drawing or an ordinary photograph.

The hologram technique invented by Denisyuk is known as single-beam reflection holography or simply Denisyuk holography [3]. The related technique of Denisyuk colour holography is used to obtain a highly realistic colour three-dimensional image of an object in which the colour rendition is as close as possible to the colour of the recorded object. As described above, holography can record and store laser light scattered off an object. Unlike earlier systems that relied on laser illumination, the scattered light captured in a Denisyuk colour hologram can be displayed by illuminating the holographic plate with a correctly positioned 'white light' source to create a three-dimensional image that is visible behind the plate and can be viewed from any angle. For museum display purposes, the large field of view (180° in both the horizontal and vertical) that can be obtained with a single-beam hologram is very attractive.

For colour reflection holography the geometry of the recording setup presents no problems, but the final result is highly dependent on the recording material used, the processing techniques applied and the lighting employed for displaying the hologram. Until panchromatic ultra-fine-grain silver halide emulsions were introduced, it was impossible to record high quality colour holograms in a single emulsion layer, but once these became available it was possible to produce such Denisyuk holograms [11].

To record full colour holograms accurately the most important issues are the number of lasers to be employed, their peak wavelengths, the material used for the recording and the selection of the best type of light source to illuminate the holographic plate for display. The last two issues can be resolved by using a low light-scattering, ultra-high-resolution material that is sensitive across the range of visible light wavelengths (panchromatic) to produce plates that can usually be illuminated with ordinary 'white light' sources. However, any serious application of holography for archival purposes requires accurate colour rendition and this depends on selecting the correct recording wavelengths. To date, most colour holograms have been recorded using three primary (red, green and blue) laser wavelengths, resulting in good colour rendition, but generating some colours that are not identical to those of the original object.

The selection of laser recording wavelengths

The starting point for recording colour holograms – using red, green and blue (RGB) primary laser wavelengths – is based on the tristimulus theory of colour vision, which assumes that any colour can be matched by a linear combination of three primaries. However, the development of the tristimulus theory was based on primaries with broader emissions than those from lasers, which produce light in a very narrow wavelength range. There have been theoretical investigations carried out to determine the minimum number of laser wavelengths needed

TABLE 1. Average colour error for the rendition of the 24 patches in the Macbeth ColorChecker® test chart using three to seven optimal laser wavelengths

Number of lasers	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

Note. Details of the procedure used to calculate the average error are given in [12].

to give a difference in colour that is small enough to be undetectable by an observer. A recent study by Bjelkhagen and Mirlis found that while using three laser wavelengths gives good colour reproduction, significantly greater accuracy can be achieved by using four to five wavelengths, but that above this number further improvement in colour rendition is minimal [12]. In that study, the results from which are summarized in Table 1, a computer simulation was used to calculate the average error in the rendition of the 24 patches in the Macbeth ColorChecker® test chart; details of the procedure used to calculate the average error are given in [12].

Recording materials

Returning to the choice of recording material, which is of equal importance to the choice of laser wavelengths when making high quality colour reflection holograms, it is necessary to use panchromatic recording materials that scatter very little light. Problems with the scattering of light, particularly at the blue end of the visible spectrum, exclude many earlier monochrome holographic materials from being used. Although silver halides have been used in holography from its invention and are among the most sensitive recording media for large-format holograms [13], there are very few materials of the silver halide type on the market that are suitable for colour holography. For such applications a distinctive type of panchromatic ultra-fine silver halide emulsion (with a grain size of *c.*10 nm or less) is needed. The manufacture of such materials specifically for colour holography was the subject of a two-year European research project, *Silver Cross*.[1] The project concluded that as materials based on silver halides had produced the results with the highest recording quality and image fidelity over the years, this technology should be chosen for the development of new emulsions for high quality colour holography.

Setup for recording colour refection holograms

As the most realistic holograms are produced by reflection holography, this technique has been used in the experimental configuration illustrated in Figure 2, which to date has only been exploited using three laser wavelengths (RGB). In the configuration used in this study the three primary recording laser wavelengths were: 476 nm, provided by an argon ion laser; 532 nm, provided by a continuous-wave frequency-doubled Nd:YAG laser; and 647 nm, provided by a krypton ion laser, Figure 3. Two dichroic beam combiners are used to provide a single 'white' laser beam that passes through the shutter and spatial filter, Figure 2. The 'white' laser beam illuminates both the holographic plate and the object itself through the plate. The three primary laser wavelengths simultaneously form individual interference patterns in the emulsion during the exposure. The use of beam combiners not only allows this simultaneous expo-

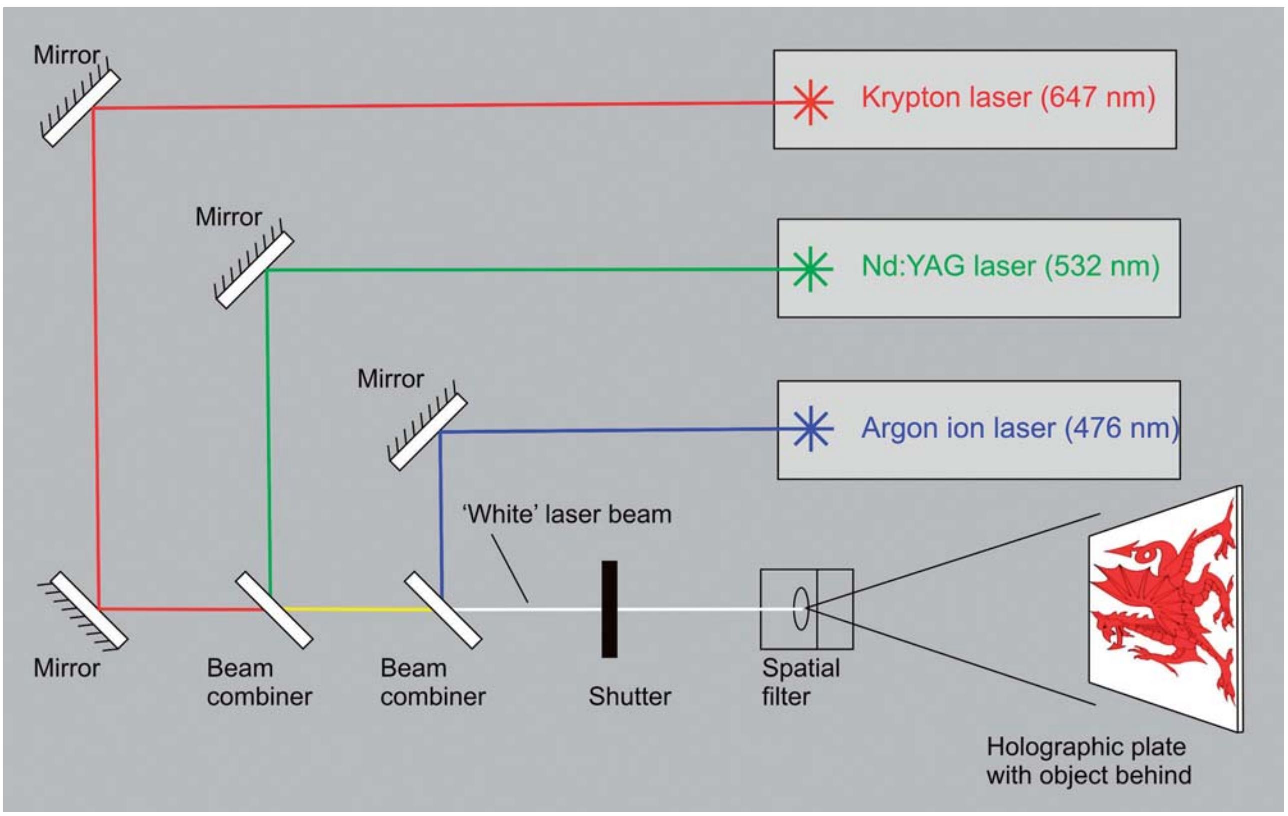

FIGURE 2. Experimental configuration used to record colour reflection holograms

FIGURE 3. The red krypton laser, the green Nd:YAG laser and the blue argon laser in the laser room at CMO

sure of the holographic plate, but also makes it possible to control independently the ratio of the three lasers and the overall exposure energy in the emulsion. The ratio can be varied by changing the output power of the individual lasers, while the overall exposure energy is controlled solely by adjusting the exposure time.

Displaying recorded holograms

A limiting factor in holography is the problem of displaying the colour holograms. The choice of a light source used to illuminate recorded holograms is of greater importance than in the case of monochrome holograms, as the colour temperature of the source has an influence on the colour rendition of the holographic image. In addition, the size of the source used to display the hologram determines the degree of 'blur' in the parts of the image that appear either in front of or behind the plane of the holographic plate. Figure 4 illustrates the image-disturbing effect of using a light that is not a point source, or multiple light sources, on a hologram. It is important that only one light source illuminates the hologram and that no other direct light hits the holographic plate, for example sunlight through a window.

Arranging the correct illuminating angle (i.e. the same reference angle that was used to record the hologram) between the holographic plate and the light source ensures that the correct colours are seen in the displayed image. To avoid any image aberrations, the distance from the 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 colour balance for the recording of a colour hologram must be adjusted bearing in mind the type of light that will be used for the display of the finished hologram and is a reason why holograms can only usually be considered in fixed display installations using, for example, specially installed track lighting with adjustable spotlights.

The rapid progress in the development of solid state lasers and light emitting diodes (LEDs) has opened up new possibilities for illuminating colour holograms. The ideal situation would be if the wavelengths of the LED light sources could match those of the lasers used to record the hologram. When using a tungsten halogen lamp, which is the common practice at the time of writing, light from a large part of the spectrum emitted illuminates the surface of the plate without having any impact on the intensity of the image. Instead, light scatter is increased, lowering the image contrast. With a combination of LEDs matched to the recording wavelengths, more effective use would be made of the incident radiation and scatter would be minimized. LED light sources have other advantages over tungsten halogen and other traditional light sources, including low running costs and long service lives.

RECORDING THE HORSE JAW HOLOGRAM

The decorated horse jaw fragment from Kendrick's Cave was one of the first objects to benefit from recording using the techniques developed at the Centre for Modern Optics (OpTIC), in St Asaph, North Wales. As part of the British Museum UK Partnership scheme, this unique object was loaned to an exhibition at Llandudno. As mentioned earlier, the jawbone has been on display at the British Museum since its acquisition in 1959, but the panels of incised zigzag lines that form a pattern on the underside of the chin are difficult

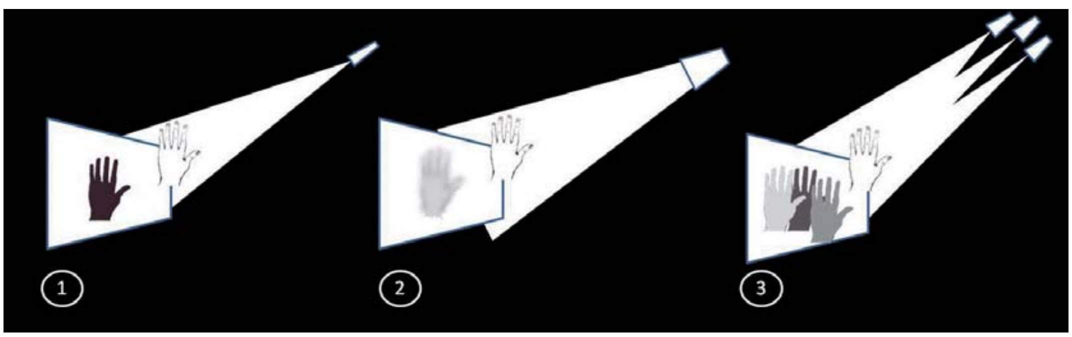

FIGURE 4. The influence of hologram illumination on the holographic image: (1) a narrow beam spotlight where the light is generated from a very small area gives a sharply focused hologram; (2) a spotlight with a wider light source size that illuminates the hologram gives a more blurred image; and (3) multiple light sources give rise to a series of holograms

to see and have always been displayed with an explanatory drawing on the label [14]. Consequently, the request from David Crane of Llangollen Museum to record a hologram to be used in the *Bringing the Artefacts Back to the People* exhibition that toured remote Welsh villages without museum facilities also offered the opportunity of experimenting with a technique that might make the decoration on the object easier to see.

After confirming that the recording laboratory offered stable environmental conditions within the temperature and humidity parameters recommended for objects made from bone, it was agreed that a hologram of the Kendrick's Cave jaw should be recorded in the presence of its curator (JC) and the fragment was taken to the OpTIC laboratory in April 2009. The recording room, containing a stable recording table (Figure 5), is adjacent to the laser room from where the white RGB laser beam passes through a hole in the wall to the recording room. The jawbone was positioned on a horizontal red-painted aluminium plate placed on the recording table. The recording holographic plate was positioned above and very close to the object, Figure 6. During the set-up stage the recording room was illuminated only by a 'safelight', to avoid fogging the unexposed recording plate. During the exposure, the divergent white laser light illuminated the object through the light-sensitive holographic plate at an angle of approximately 45° for an exposure time of 25 seconds. Because of the long exposure time the object and the recording equipment must be stable. When continuous wave lasers are used for the recording, as is the case here, only stable artefacts can be recorded. If the object is soft or unstable, pulsed RGB lasers – like the ruby laser used to record the Lindow Man hologram – are needed. These emit a high intensity, very short pulse of laser light with a duration of 20 to 30 ns and are analogous to the high intensity, short duration flash used in conventional photography. Several original holograms were recorded during the day that the jawbone was in the laboratory.

After exposure the plate has to be developed in a darkroom; wet processing of the plate includes developing, washing, bleaching and finally drying. After processing, a transparent phase hologram is obtained; this finished hologram resembles a sheet of glass with nothing visible on the plate itself. Before the hologram can be displayed a black backing needs to be applied. In addition, the surface of the plate is sealed under glass to protect the emulsion. An image of the recorded hologram is shown in Figure 7, but it should be noted that this two-dimensional representation cannot reproduce the qualities of the hologram itself. As with all such holograms, the quality of the Kendrick's Cave horse jaw hologram can only be fully appreciated by viewing it under appropriate display conditions.

The latter image is a remarkable three-dimensional reproduction that makes the engraved pattern on the jawbone clear. Although it is always preferable to lend and display the object itself, where facilities do not permit this, the hologram offers a good alternative that is more intriguing and tangible than a two-dimensional image. Although venues must be able to display holograms with correctly positioned light sources, in some remote places this is considerably easier than providing the sometimes exacting environmental conditions recommended for

FIGURE 5. The recording room at CMO, which is adjacent to the laser room. The heavy table floats on air cushions, while the recording area is surrounded by polyethylene foam blocks that isolate the object from air turbulence. The power meter at the centre is used to measure the light emitted from the lasers

FIGURE 6. The Kendrick's Cave horse jawbone set up for holography on the red surface of the recording table

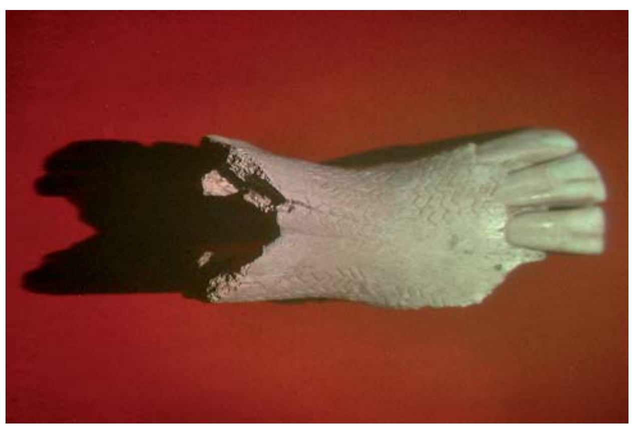

FIGURE 7. Two-dimensional image representing the hologram of the Kendrick's Cave jawbone

delicate objects – often requiring the use of display cases – and additional security measures. These considerations have been key factors in developing the colour holography project *Bringing the Artefacts Back to the People*, which involves collaboration with a number of major institutions, including the National Museum of Wales, the British Museum, the Maritime Museum in Liverpool and the Royal Commission for Ancient and Historical Monuments in Wales. Recording of holograms of all the artefacts to be included in the exhibition was completed by the end of 2009 and the travelling exhibition toured North Wales and the borders, starting at Llangollen and continuing in Chester, Wrexham, Llandudno, Bangor and Llangefni.

CONCLUSIONS

The virtual colour image behind a holographic plate represents the most realistic three-dimensional image of an object that can be recorded currently. 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 visible spectrum good colour rendition can be achieved. The wave front reconstruction process recreates accurately the laser wavelengths scattered by the object during the recording of the hologram. This three-dimensional imaging technique has many obvious applications, in particular displaying unique, precious or expensive artefacts. The application of colour holography to the *Bringing the Artefacts Back to the People* project is an example of how museums and the tourist industry can take advantage of this new imaging technique and probably represents the first museum exhibition created entirely from colour holograms. A similar project is underway in Greece where important antiquities and works of art are being recorded using Denisyuk holography for touring to remote regions and tourist resorts [15].

Evaluation of the public response to such touring shows will inform how the use of this kind of technology might be developed. At the Origins Centre, a museum on the campus of the University of Witswatersrand in Johannesburg, South Africa, a monochrome hologram is used in the display of a 79000-year-old red ochre object decorated with an incised pattern. Encouraged by a 'please touch' sign, visitors reach out for what appears to be the real object and this action triggers a three-dimensional video in which archaeologist Christopher Henshilwood describes finding this extremely ancient art object in Blombos Cave. Rather than simply being a gimmick the video holds the attention of visitors of all ages who might not otherwise be attracted to the object. The key factor in this case is that the hologram and video were designed as integral components of the exhibition not just as add-ons. Persuading curators and designers to consider the use of holography in this way is possibly the best way forward in the application of the technique, the future use of which will also depend on cost effectiveness and the development of portable recording equipment.

Colour holography offers a route to novel display techniques and enables artefacts too fragile for normal display to be shown. It is applicable not only to three-dimensional objects but also may be used for two-dimensional objects such as oil paintings [16]. Holograms will not fade or change colour even if they are continuously on display, suggesting a potential application for the reproduction and exhibition of vulnerable textiles. Overall, holography offers a means of reproducing rare or high-value artefacts so that they can be displayed under circumstances where normal museum protocols would prevent their exhibition.

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NOTE

1. The *Silver Cross* project, European EC FP6 CRAFT project 005901, was carried out between 2004 and 2007.