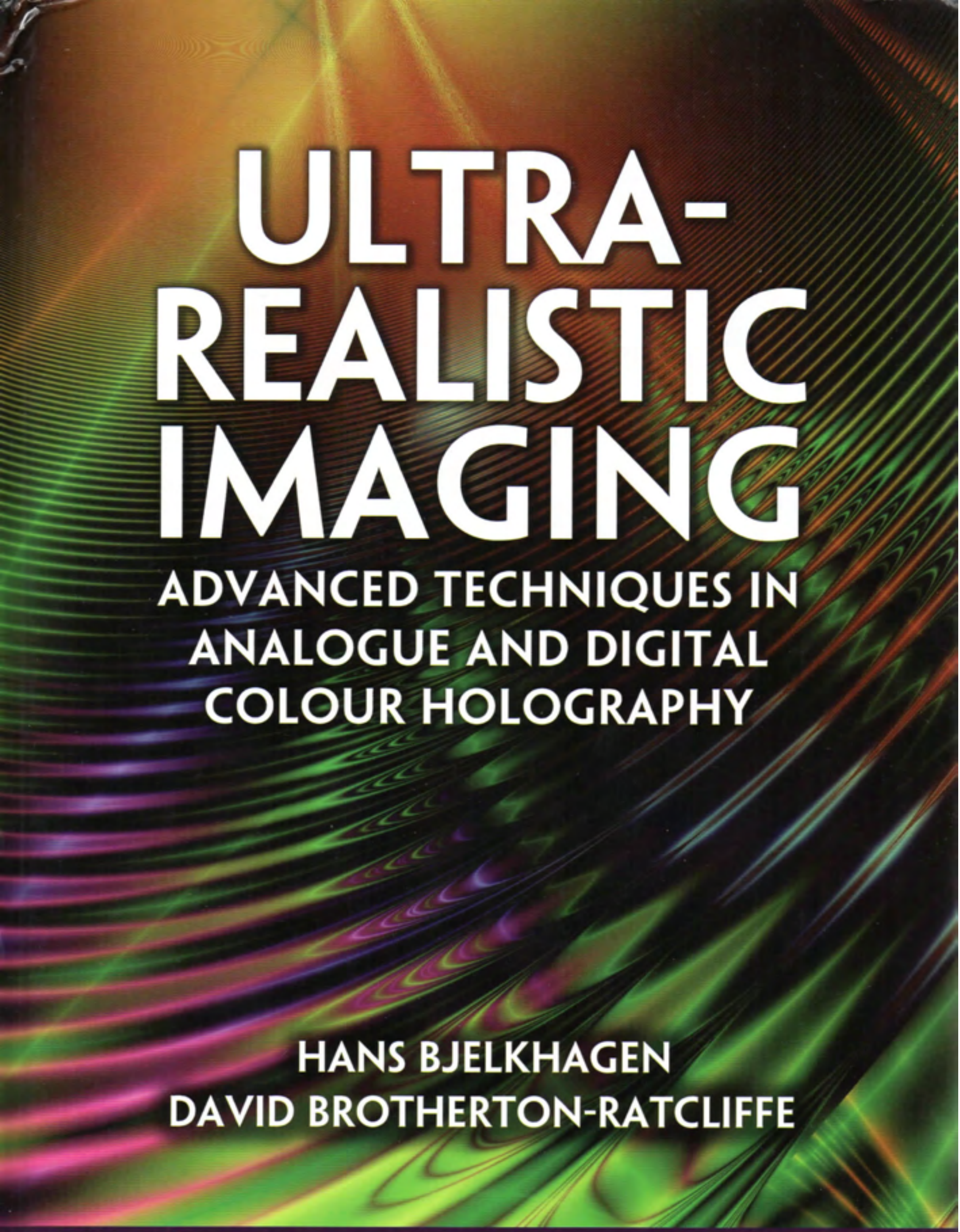

ULTRA-REALISTIC IMAGING

ADVANCED TECHNIQUES IN ANALOGUE AND DIGITAL COLOUR HOLOGRAPHY

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FIGURE 13.21 Lytespan Mini LED. (Photo courtesy of Philips Lightolier.)

FIGURE 13.22 Definity PAR38 LED lamp. (Photo courtesy of Lighting Science Group.)

is the socket-able LED light engine, which fits GE's Infusion module and Phillips' Fortimo spotlight module. Another example of a white phosphor-type LED spotlight is the Lytespan Mini LED manufactured by Philips Lightolier [14] (Figure 13.21), which offers excellent beam control. Interchangeable optics also provide flexibility to adjust the lighting. Finally, Lighting Science Group, Satellite Beach, FL [15] manufactures a new family of 18 to 24 W LED lamps, the Definity lamps, which are intensely bright (lumen output, 840–1460 lm) all in one package shown in Figure 13.22.

13.3.6.11 Special LED Spotlights for Colour Holograms

In Greece, 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, Athens, Greece [16] and is commercialised by TAURUS SecureSolutions Ltd., Athens, Greece [17]. 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 full-colour reflection holograms.

The device consists of an illuminating head, extending arms and a mounting base. The illuminating head contains the RGB LEDs, mixing optics, lenses and heat sinks. The system has an embedded microcontroller for intensity control of each LED with DMX protocol decoding and a miniature wireless receiver. Remote adjustment of the colour mixing by DMX protocol communication is achieved by a handheld wireless remote control. A small switching power supply provides the power needed for EU or US mains.

The optics incorporated in the unit provide for an axial mixing of the LED beams resulting in a homogeneous colour mixing over the full extent of the projected beam. The small footprint of the LED die (~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 that 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 (see Chapter 14).

- Red 620–630 nm
- Green 520–535 nm
- Blue 450–465 nm

The LED spectrum of the HoLoFoS illuminating system is shown in Figure 13.23 and the LED spotlight with its colour control box is shown in Figure 13.24.

To demonstrate the advantage of using this LED light for displaying colour holograms, the same hologram was illuminated with a conventional halogen spotlight and the new HoLoFoS LED light; the results are shown in Figure 13.25a and b. Note the increased contrast obtainable with the new LED light. This is also a good illustration of the vital importance of the illumination source in holography. Pulsed digital holograms, which are often printed using a red wavelength of 660 nm, require a version of the HoLoFoS light with a deeper red diode.

LED spotlights such as the HoLoFoS light can also be mounted in stacks for the illumination of HPO reflection holograms as described in Section 13.1.3.

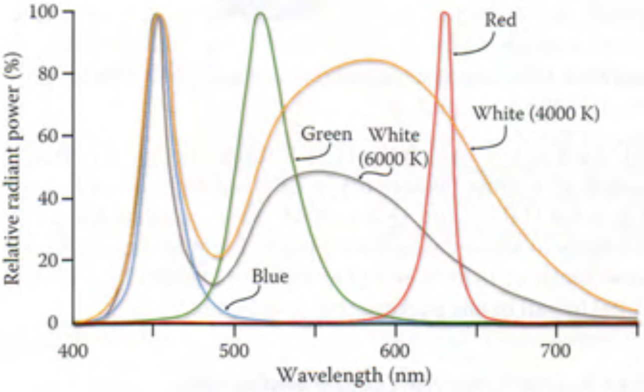

FIGURE 13.23 The LED spectrum of the HoLoFoS illuminating system.

FIGURE 13.24 The HoLoFoS LED spotlight for the illumination of colour holograms.

sigmoidoscope) was performed to obtain *in vivo* holograms of the colon of an anaesthetised dog [24]. The principle of the fibre coupler colour laser combiner is shown in Figure 14.5, the prototype holoendoscope is illustrated in Figure 14.6, and a microscopic photograph derived from an *in vitro* endoscopic colour hologram of human endothelial cells is shown in Figure 14.7.

14.3 Visual Applications of Full-Colour Holographic Imaging

In this section, we focus on current applications of the technologies of full-colour analogue hologram recording (as described in Chapter 5) and digital holographic printing (Chapters 7–10). Despite holography now being more than 60 years old, many of these applications are in an early stage of market development. This is really because the technology improvements that we have presented in this book have, in many cases, only recently led to a positive reassessment of old ideas.

14.3.1 Holographic Copies of Museum Artefacts

In the days of the British Empire, museums filled their collections with exotic items from around the world. British museums today still possess large collections from foreign countries, but there is increasing pressure to repatriate priceless artefacts to their respective homes. Holography now offers the possibility to essentially duplicate such artefacts—and to a point where observers practically cannot tell whether they are 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. Of course, the real exhibit potentially allows future scientific tests to be performed on an artefact to verify scientific theories—such as CAT scans, material testing and non-visual spectral analysis—but analogue holography does offer a means to preserving a faithful visual recording of unprecedented microscopic detail.

We should mention 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 a million 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 (~250 μm), it can nevertheless be very difficult for an observer to tell the difference between an analogue and a digital hologram with the unaided eye. The digital hologram also 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 lifetime problems. In addition, the same image data can be used to produce holograms of small and very large sizes. Thus, museum exhibits can be displayed 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 in later sections. 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. Transporting priceless artefacts, however, 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?

14.3.1.1 Virtual Museum Exhibitions

One interesting colour holography project,† which was recently carried out by the Centre for Modern Optics in North Wales, was a project funded by the Esmee Fairbairn Foundation entitled *Bringing the*

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[*] See Chapter 10 for a discussion of holocam systems.

[†] One of the authors (HB) was involved in this project.

Artefacts Back to the People. The project involved collaborations with a number of major museums including the National Museum of Wales, the British Museum, the Maritime Museum in Liverpool, as well as the Royal Commission for Ancient and Historical Monuments in Wales. Full-colour holograms of various artefacts were recorded using the analogue techniques described in Chapter 5. The holograms were completed by the end of 2009, after which they were displayed as a travelling exhibition that 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 [25].

One of the recorded artefacts, supplied by the British Museum, was a 14,000-year-old decorated horse jaw bone from the Ice Age, or late glacial period of Britain [26]. The recording setup is shown in Figure 14.8 and the hologram in Figure 14.9. Another hologram recorded was the *Tudor Owl Jug* and *Sergeant at Arms Ring* shown in Figure 14.10. These artefacts were from the Grosvenor Museum in Chester, United Kingdom. In total, ten full-colour holograms of different artefacts were included in the touring museum exhibition (Figure 14.11).

FIGURE 14.8 Horse jaw recording setup.

FIGURE 14.9 Decorated horse jaw hologram.

FIGURE 14.10 Hologram of the *Tudor Owl Jug* and *Sergeant at Arms Ring*.

FIGURE 14.11 Exhibition of the artefact colour holograms at the Llangollen Museum in Wales, 2010.

14.3.1.2 Museum Holography in Greece

In Greece, the Hellenic Institute of Holography has recently invested in a full-colour recording facility and is currently promoting *Realistic Colour 3D Holography*, according to its director Alkis Lembessis [27]. The primary goal of the Hellenic Institute of Holography 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 2011, the institute built a small, portable three-colour analogue holographic camera, the Z3 RGB Holography YSB1 prototype camera, which it is now using to record holograms of museum artefacts (Figure 14.12). The camera is a computer-controlled optomechanical device capable of exposing selected, commercially available or experimental, panchromatic silver halide emulsions to combined red, green and blue CW laser beams at appropriate energy levels. The device consists of a main camera unit (MCU) and a control electronics unit (CEU). The MCU is built on top of a lightweight aluminium honeycomb optical board to ensure portability, minimum spatial deformation under nominal temperature variation and fast damping of induced vibrations.

There are three lasers housed in the MCU with wavelengths selected to cover a broad triangle of hues in the Commission Internationale de l'Eclairage (CIE) chromaticity diagram.

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

The lasers produce TEM_{00} emissions with coherence lengths of more than 5 m each, and the MCU contains suitable optics to generate a clean collinear mixed RGB beam.

The CEU houses all power supplies, A/D and D/A subsystems plus a specially designed F/P scanning interferometer for beam monitoring. The CEU also connects to an external PC running custom software to control all aspects of the holographic exposure plus full monitoring and tuning of each laser's stability and beam quality.

The Z3 has been successfully tested under wide ambient temperature and humidity ranges. The system becomes stable after 30 min to 1 h, depending on the ambient temperature. At 24°C, the system stabilises after 20 to 30 min. The Z3 camera is accompanied by auxiliary equipment for beam orientation and a flexible vibration-absorbent setup for the positioning of the object. One example of a hologram recorded with the camera is shown in Figure 14.13. The Hellenic Institute of Holography has also produced a portable darkroom for on-site processing (Figure 14.14).

In addition to recording their own holograms with the Z3, the Hellenic Institute of Holography has produced museum holograms in collaboration with Yves Gentet (Figure 14.15) and the Colour Holographic Company in London.

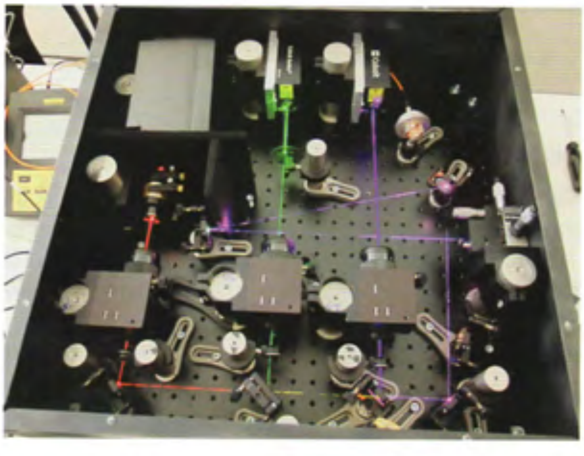

FIGURE 14.12 Z3 prototype portable RGB camera (model YSB1) made by the Hellenic Institute of Holography.

FIGURE 14.13 Full-colour Denisyuk reflection hologram made using the Z3 prototype portable RGB holography camera produced by the Hellenic Institute of Holography.

FIGURE 14.14 Andreas Sarakinos and Alkis Lembessis in front of the portable darkroom produced by the Hellenic Institute of Holography.

FIGURE 14.15 Full-colour Denisyuk reflection hologram of a Greek ceramic vase made by Yves Gentet. This analogue hologram was made in collaboration with the Hellenic Institute of Holography. The right-hand photograph shows an enlarged detail.

14.3.1.3 Museum Holography in England

In 2010, the Colour Holographic Company in London started to record colour holograms on their own ultrafine-grain panchromatic material. Some examples of the full-colour museum holograms that they have produced on this material are shown in Figures 14.16 and 14.17. A new product that 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

FIGURE 14.16 Full-colour Denisyuk reflection test hologram made by Colour Holographic Ltd.

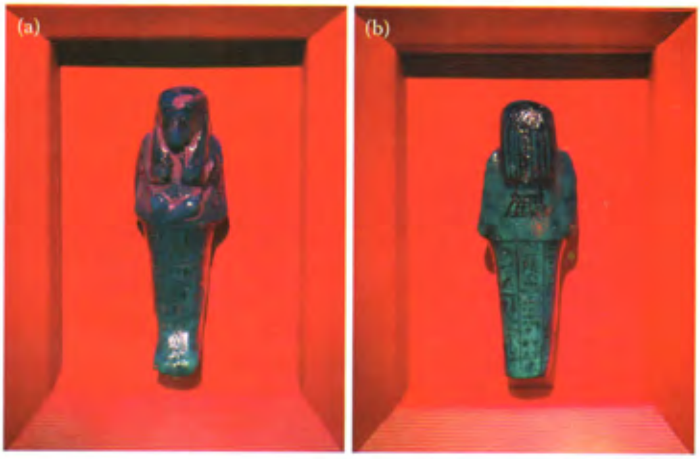

FIGURE 14.17 Full-colour Denisyuk reflection hologram made by Colour Holographic Ltd. The hologram shows (a) the front and (b) back of an Ushabti figure from the Theban cache of royal mummies found in 1881.

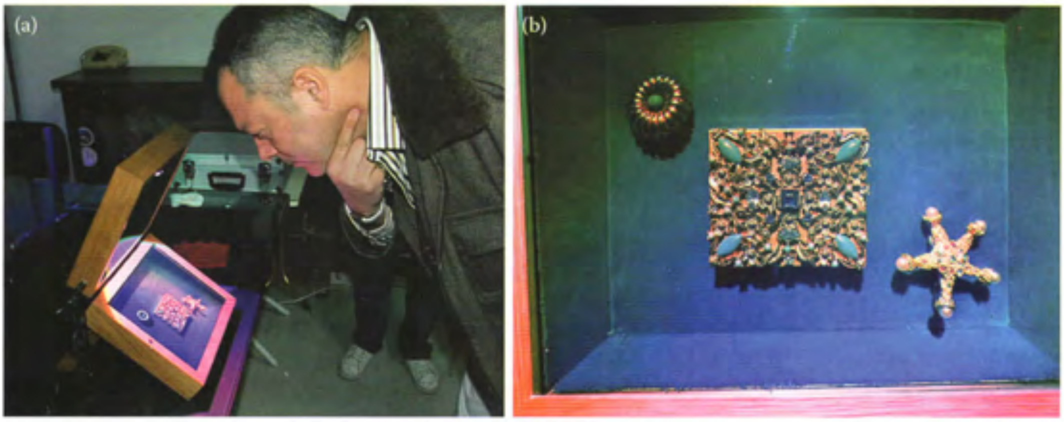

FIGURE 14.18 (a) Colour Holographic hologram box and (b) colour hologram.

possible to switch holograms and the company offers the box with different holograms for sale. The box and a colour hologram are shown in Figure 14.18.

14.3.1.4 Holographic Reproduction of Oil Paintings

Full-colour holographic copies of oil paintings offer another interesting application. Because the depth of the recorded image is essentially dictated by the thickness of the brushstrokes, this type of quasi two-dimensional recording can be rather easier to illuminate than conventional holograms. For example, source-size blurring is much less of an issue here. Holographic copying provides a method of producing copies of valuable or priceless paintings, which is unlike any other technique. An oil painting does not look the same from every angle and a photographic reproduction only records the view from straight ahead. A holographic reproduction, on the other hand, faithfully records how the light reflects at all angles, as well as accurately reproducing the relief of the brushstrokes.

One of the authors (HB), working with Dalibor Vukičević, introduced this potential application in 2000 [28]. An example of a *still life* oil painting (20 cm × 25 cm), which was copied using this technique, is shown in Figure 14.19a. The painting was selected mainly because it was painted on

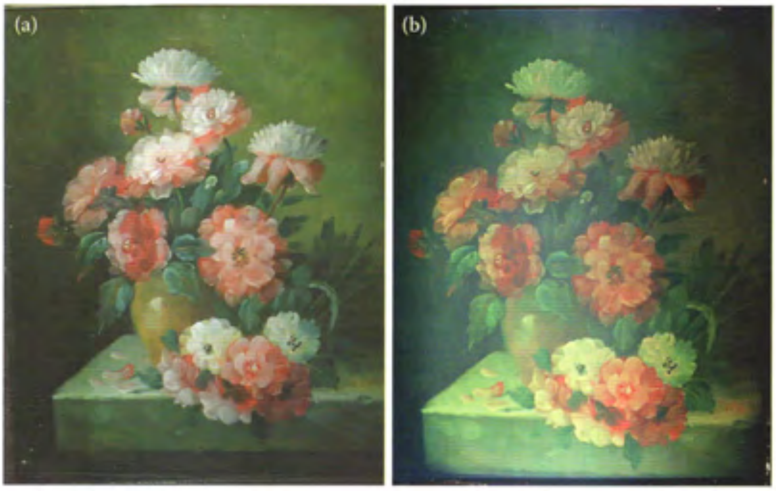

FIGURE 14.19 (a) Oil painting and (b) full-colour analogue Denisyuk reflection holographic reproduction.

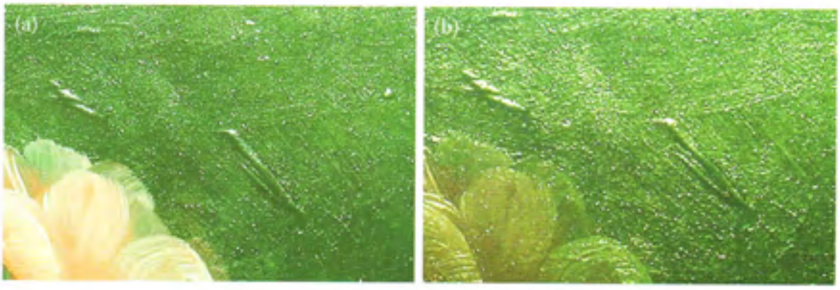

FIGURE 14.20 (a) Detail of brush strokes in the oil painting of Figure 14.19a and (b) in the holographic reproduction of Figure 14.19b.

FIGURE 14.21 Higher magnification of brush strokes in the hologram of Figure 14.19b.

wood* with a pronounced surface texture. A Denisyuk single-beam three-colour holographic setup (described in Chapter 5) was used to record the colour hologram onto a Slavich panchromatic PFG-03C silver halide plate (Figure 14.19b). A detail of the painting texture, visible when observed at a certain angle, is shown in Figure 14.20a. The same surface texture visible in the hologram is shown in Figure 14.20b. The holographic reproduction can be studied in more or less the same way as the real painting can be investigated. Brush strokes, visible in the hologram under high magnification, are illustrated in Figure 14.21.

Colour holograms of paintings have also been demonstrated by Yves Gentet, who recently took recording equipment to the Louvre in Paris to demonstrate the potential of this new reproduction technique. A transportable holographic camera is often required in applications regarding the recording of items of significant cultural heritage, including oil paintings—often because the item in question simply cannot be moved due to insurance or security reasons. Gentet and Shevtsov [29] were the first to develop a small, mobile full-colour analogue holographic camera system especially for this purpose. Much like the system currently used by the Hellenic Institute of Holography, Gentet and Shevtsov's system is based on three solid-state continuous wave lasers: a semiconductor red laser at 639 nm giving 25 mW, a diode-pumped solid-state laser at 532 nm giving 120 mW and another diode-pumped solid-state (Cobolt) laser at 473 nm giving 70 mW. The overall dimensions of the camera system, which allows a hologram format of up to 30 cm × 40 cm to be recorded, are 30 × 40 × 50 cm with a weight of 12 kg.

In copying oil paintings and indeed other cultural heritage items, the reproduction of spectral information is of particular importance. As we mentioned in Chapter 5, three-colour analogue holograms produce a good, but certainly not perfect, spectral representation. Future work will hopefully extend holographic copying to four or five wavelengths.

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* With the available lasers at the time, wood provided better interferometric stability.

Appendix 9: Recent Developments

A9.1 New Equipment, Materials, Techniques and Applications

After the manuscript of this book was submitted for typesetting, inevitably new advances in equipment, techniques, and applications came to the authors' attention. Before publication, we were pleased to have the opportunity to include this final appendix, which we believe brings the book properly up to date as of October 2012.

In Chapter 2, we described Lippmann photography and discussed interferential structures in nature. In September 2012, an interesting paper was published revealing that such structures exist not only in insects and butterflies but also in plants. Vignolini et al. [1] present a striking example of multilayer-based strong iridescent colouration in plants, in the fruit of *Pollia condensata* (Figure A9.1). The fruit contains helicoidally stacked cellulose microfibrils that form multilayers in the cell walls of the epicarp. Because the multilayers form with both helicoidicities, optical characterisation reveals that the reflected light from every epidermal cell is polarised circularly either to the left or to the right, a feature that has never been previously observed.

Important papers were presented at the *9th International Symposium on Display Holography* (ISDH 2012) in June 2012 at MIT, which also need to be mentioned here. The reader is referred to the conference website [2] where video presentations [3] and proceedings can be accessed. Zebra Imaging Inc. described a new simple way of capturing 3D information intended for digital colour holograms. Zebra is now offering a printing service based on the technique for people interested in making their own digital colour holograms.

In association with the ISDH conference, there was a hologram exhibition arranged at the MIT museum. One of the exhibited holograms that drew particular attention was a digital achromatic reflection hologram, printed by Geola. The hologram was a new version of the holographic portrait of Queen Elizabeth II, created by the artist Chris Levine and holographer Rob Munday, and demonstrated clearly that high-quality black-and-white holograms can be made using the DWDH technique described in this book. The Queen's portrait was also featured on a recent postage stamp from Jersey Post.

Progress in solid-state CW and pulsed lasers has been rapid, and accordingly, there are now various improved laser systems on the market that are suitable for recording colour holograms.

Progress in recording materials and recording techniques has been made on two fronts. Firstly, a new recording principle for colour holograms based on *surface plasmon waves* has been reported, although more development work will be needed before the technique can become a practical recording method for colour holograms. Additional progress in recording materials has come from Geola, where high efficiency DWDH holograms have recently been written onto photoresist using single nanosecond pulses at energies 10 times smaller than those usually required using conventional CW exposure.

Holografika introduced a new improved HoloVizio™ 3D holographic system at the *Siggraph 2012* Las Vegas exhibition in August 2012. The technique behind Holografika's products has been mentioned in Chapter 14, but the recent products and improvements are worth including here. The company SeeReal in Germany has also reported progress in their VISIO 20 real-time 3D holographic display system.

a real existing object in a viewing window at the eye position. In the company's device, the viewing window is the Fourier transform of the hologram and may be as small as the eye pupil. To get over the lack of resolution available, the viewing window is tracked to the eye position (Figure A9.13). The object size is therefore only limited by the hologram size and not by the hologram resolution. 3D scenes extend from in front of the display to a great depth behind the display. In the colour version of the display, RGB lasers are used with sequential multiplexing so that one laser wavelength at a time illuminates the display screen with its corresponding interference pattern. Figure A9.14 shows an example of a displayed colour image.

A9.8 New Holography Camera from the Hellenic Institute of Holography

The Hellenic Institute of Holography (HiH) in Athens has completed the latest version of its commercial transportable camera Z3^{RGB} (model: ZZZyclops, shown in Figure A9.15). The details of the camera design have been described in Chapter 14. The camera is now ready for use in museums around the world. The ultrarealistic Denisyuk colour holograms recorded by the camera are marketed by HiH as OptoClones©. HiH also reported that they have originated a full-colour DWDH holographic map of the island of Kos in Dodecanese (printed by Geola, size 50 cm × 130 cm) on commission from the Greek Infantry Geographical Services using real GIS data and on permanent exhibition at their museum in Athens. More recent information was provided by Lembessis at the *2012 Holo-pack-Holo-print* conference in Austria [14].

A9.9 HoloKit from Liti Holographics

Finally, we should mention that Liti Holographics Inc., Newport News, VA [15], is offering a digital hologram printing service for application within the retail signing, merchandising and point of purchase markets. Liti Holographics is also a manufacturer of HoloKits (small complete kits for making holograms), and in 2012, Liti introduced a new kit for making colour reflection holograms. The kit contains three small (RGB) lasers to record 2 inch × 3 inch holograms on a panchromatic photopolymer material.

FIGURE A9.15 HiH transportable camera Z3^{RGB}. (Courtesy of Hellenic Institute of Holography.)

Physics

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Ultra-high resolution holograms are now finding commercial and industrial applications in such areas as holographic maps, 3D medical imaging, and consumer devices. **Ultra-Realistic Imaging: Advanced Techniques in Analogue and Digital Colour Holography** brings together a comprehensive discussion of key methods that enable holography to be used as a technique of ultra-realistic imaging.

After a historical review of progress in holography, the book:

- Discusses CW recording lasers, pulsed holography lasers, and reviews optical designs for many of the principal laser types with emphasis on attaining the parameters necessary for digital and analogue holography
- Gives a full review of current photosensitive materials for colour holography
- Covers modern methods of analogue holography and digital holographic printing
- Introduces mathematical and geometrical notation for horizontal parallax-only holograms and practical computational algorithms for the full-parallax case
- Reviews systems and the image processing algorithms required to convert the raw image data to the format required by digital printers
- Develops the physical theory of the holographic grating and the hologram
- Provides an up-to-date review of illumination sources, including LED and laser diode sources

Written by leaders in dynamic holography, this handbook provides complete coverage of real-time colour holographic processes, including applications. The book covers not only the optics and theory behind such holographic systems, but also laser technologies, recording devices, data acquisition and processing techniques, materials for reproduction, and current and developing applications.

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