ULTRA-REALISTIC IMAGING

ADVANCED TECHNIQUES IN ANALOGUE AND DIGITAL COLOUR HOLOGRAPHY

HANS BJELKHAGEN
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Foreword

It is my pleasure to write the Foreword to this book. I have known the authors, as well as their professional accomplishments in this field, for three decades.

Hans I. Bjelkhagen has devoted his entire professional life to holography. He is most well known for advancing the fields of silver-halide materials and their processing, interferometry, pulsed portraiture, Lippmann photography, and ultrarealistic color holography. He taught annual summer workshops at Lake Forest College from 1982 to 1997 that included courses on color holography, photochemistry, and pulsed portraiture.

As leader and organizer, Bjelkhagen cochaired with me the triennial International Symposium on Display Holography (ISDH) until I retired in 1997. In 2005, he revived and chaired a successful ISDH in the United Kingdom. With this encouragement, we held an ISDH in China in 2008, where he was a cochairman. He also helped organize the 2012 ISDH at the Massachusetts Institute of Technology. He is the current chairman of the annual Practical Holography Conference in California sponsored by the International Society for Optical Engineers (SPIE). Less well known is that he is a meticulous collector of all information pertaining to holography, maintains a detailed directory on holographers past and present, and collects holographic postage stamps that have been issued internationally.

David Brotherton-Ratcliffe is a polymath whose career spans both theoretical and experimental sciences including plasma physics, magnetohydrodynamics, nuclear fusion, laser engineering, diffractive optics, holography, and advanced systems design for the recording and production of both analogue and digital large-format holograms. His recent work in pulsed laser portraiture systems and computer-generated full-color, full-parallax holograms as presented in this book is truly state-of-the-art.

An abundance of books and articles on holography at the elementary level have already been published over the years since the mid-1960s. It is not necessary to repeat their contents here. This book is a condensation at the highest level of the authors' collective knowledge and experience in the area of display holography that includes history, theory, practice, and detailed designs of industrial systems. It includes over 500 photographs, diagrams, and design schematics for the recording and production of ultrarealistic holographic images.

Tung H. Jeong

Preface

Ultra-Realistic Imaging may be defined as any imaging technique that is able to record and reconstruct the visible electromagnetic light field scattered from a real-world object or scene with a resolution better than or equal to that of the unaided human eye. This book is devoted to a discussion of how the goal of ultra-realistic imaging may be attained through the application of the interferential methods of modern analogue and digital holography—and in particular through volume phase holography.

Holography was discovered more than 60 years ago. With the discovery of the laser and the off-axis technique in the early 1960s, it very quickly became obvious that the method constituted a unique imaging principle with enormous possibilities. However, the quality of the holographic image depended intrinsically on many things—such as the photosensitive material, the chemical processing scheme, the recording laser and not least, the illumination source with which the recorded hologram had to be viewed. This innate dependence of holography on critical associated technologies has been responsible for the waves of great enthusiasm for the subject being followed by periods of equally great disillusionment.

Holography has of course had its successes. The embossed security hologram and packaging industries are testament to this, but the role of holography as a technique of true ultra-realistic imaging is only just now becoming possible. This has been due to great progress in the key associated technologies of photosensitive materials, recording lasers, light sources, spatial light modulator technology and computers.

Digital techniques in holography are particularly exciting. Very large, high-definition full-colour holograms can now be written as a matrix of tiny elementary holograms, rather like a modern high-definition television screen is made up of pixels. One of the applications becoming possible with this technology is the creation of high virtual volume (HVV) displays. These are full-colour, full-parallax holograms that can replay 3D scenes having volumes from tens of cubic metres to cubic kilometres. Well-known holographers such as Nick Phillips and Paula Dawson took the first steps towards this type of display in the 1970s and 1980s using analogue laser transmission holography. Virtual volumes of tens of cubic metres were realised, but the images were noisy, monochromatic and had to be illuminated by bulky lasers. The new digital HVV holographic displays will have none of these deficiencies. In their ultimate incarnation, HVV displays can be used to create virtual holographic windows—these are ultra-realistic displays that seek to mimic a real window with a virtual 3D scene. As "space with a view" becomes an ever more costly commodity within the context of humanity's inextricable progression to increasingly high-density urban environments, holographic windows may well provide a valuable solution.

Such applications are of course simply light-years away from the conventional holography that most people are used to today. This radical transformation is only becoming possible now because of great progress in many associated fields. The information content of an HVV hologram is enormous—the required image processing has simply not been practical until recently. Likewise, the image data could not be written to a hologram at a sufficiently high resolution without the recent progress in HD spatial light modulator technology. Panchromatic photosensitive materials of sufficient resolution were not previously known. And compact narrowband laser and LED illumination technology was not available for the illumination of such displays.

This book is certainly not intended as a basic introduction to holography. There are already many excellent books fulfilling this need. Rather, it brings together a discussion of key methods that enable holography to be used as a technique of ultra-realistic imaging.

The book starts with a historical review of progress to date in holography. We felt that this was merited from a contextual point of view and we have also taken the liberty to document some of our personal work here. Chapter 2 is devoted to Lippmann photography. This 100-year-old interferential colour photographic technique is relatively unknown, but Lippmann photographs offer exceptional colour fidelity. When Lippmann photography was introduced by Gabriel Lippmann, the impression his type of colour images made on photographers of the day was clearly expressed by Edward Steichen who wrote to Stieglitz in 1908:

> Professor Lippmann has shown me slides of still-life subjects by projection, that were as perfect in colour as in an ordinary glass positive in the rendering of the image in monochrome. The rendering of white tones was astonishing, and a slide made by one of the Lumière brothers, at a time when they were trying to make the process commercially possible, a slide of a girl in a plaid dress on a brilliant sunlit lawn, was simply dazzling, and one would have to go to a good Renoir to find its equal in colour luminosity.

A discussion of CW recording lasers for holography is given in Chapter 3. This has been an area of great progress and there is every reason to expect that such progress will continue at an even greater rate into the future. Small DPSS and semiconductor lasers can now be integrated into portable full-colour holographic cameras. Such systems have potential for use in areas such as museum archives. Museums such as the British Museum in London and the Louvre in Paris have shown real interest here. Pulsed holography lasers are reviewed in Chapter 6. Recent progress in RGB pulsed laser design has been instrumental in achieving high-quality digital colour holograms; pulsed lasers constitute a crucial technology for HVV displays. Detailed optical designs are reviewed for many of the principal laser types with emphasis on attaining the parameters necessary for digital and analogue holography.

A full review of current photosensitive materials for colour holography is given in Chapter 4. Such materials are totally key to ultra-realistic holographic imaging. Some great materials are available today and there are indications that further progress will occur in the field. For example, processing-free photopolymers with index modulations approaching and even surpassing those observed in dichromated gelatin have been discovered. Modern methods of analogue holography are covered in Chapter 5; the latest work in this field has demonstrated the production of holograms that are almost indistinguishable from real objects. Work has underlined the importance of choosing the correct recording lasers here and progress in laser engineering has greatly helped this field.

Chapter 7 is devoted to the relatively new but extremely exciting field of digital holographic printing. Digital holographic printing is distinct from computer-generated holography (CGH). Here, we describe the detailed design of various types of digital holographic printers. We explain how ultra-realistic volume phase holograms may be printed as a matrix of elementary volume holograms using computer image data. Unlike CGH, each elementary volume hologram is created by an optical interference process. We discuss the generation of HVV displays and the design of HVV printers. The image processing algorithms required for the different types of digital holograms are developed in depth in Chapters 8 and 9. Chapter 8 introduces the mathematical and geometrical notation but is otherwise devoted mostly to horizontal parallax-only holograms. Chapter 9 deals with practical computational algorithms required for the full-parallax case.

3D image data acquisition systems must be used when digital holograms are to be printed of real-world objects or scenes. The most popular type of system is the *Holocam*—a camera on one or more motorised rails. These systems and the image processing algorithms required to convert the raw image data to the format required by digital printers are reviewed in Chapter 10. Other techniques such as structural light are also reviewed.

Chapters 11 and 12 are devoted to physical theory of the holographic grating and the hologram. Here, we develop various models from first principles. Paraxial and fully non-paraxial formulae are derived for image distortion, image blurring and chromatic aberration. Kogelnik's coupled wave theory is derived from first principles and expressions for diffractive efficiency are given. We also review N-coupled wave theory and discuss the question of diffuse holograms and polychromatic gratings. Of special interest is Chapter 12, which describes a new theory capable of treating the polychromatic grating as an infinity of parallel stacked mirrors. This theory lends a useful insight to the interpretation of Kogelnik's model—an issue which is not usually taken up in standard texts but which is nevertheless of some importance for a proper understanding of the process of holographic diffractive reflection and transmission.

Illumination sources are of fundamental importance to holography as they dictate how the holographic image replays. We give an up-to-date review of these sources in Chapter 13. Of particular importance are the new LED and laser diode sources. These devices are characterised by a much smaller value of étendue, a high power and a narrower bandwidth. They may be expected to improve, in a rather fundamental way, the displayed image properties of the polychromatic volume reflection hologram.

Finally, Chapter 14 contains a review of some of the most important applications of ultra-realistic holography. We include a section on scientific imaging where holographic microscopy, holography endoscopy and bubble chamber holography are discussed. Sections are also included on how digital holography can be used in advertising and display, urban planning, military mapping and architecture. Analogue holography is discussed in relation to its increasing interest from museums as a vehicle for both archival and travelling exhibitions. The book ends with a section on updateable and real-time digital full-colour holographic displays.

We have included a number of (mostly technical) appendices that should be of interest to workers in the field. Wherever possible in the book, we have tried to include enough detail so that the experienced reader may actually start using the techniques described. It is the authors' hope that this book will fill a gap that currently exists in the technical literature by providing a comprehensive treatment of holography and its key associated fields in the context of ultrahigh-fidelity full-colour imaging. By necessity, familiarity with a number of relatively advanced topics is assumed. Some of the chapters are completely non-mathematical; others, such as Chapters 8 through 10, despite the apparent complexity of expressions, only require a basic knowledge of mathematics. Chapters 11 and 12 probably require a slightly deeper knowledge, but nothing more than the mathematics learnt at the second or third year of a typical undergraduate course in mathematical physics. The book is, however, designed to be relatively modular and omission of the more mathematical chapters should not, in general, preclude a reading of the less mathematical ones.

Finally, we should point out that we have included within the book a number of photographs of holograms. In many previous books, it has always been possible to discriminate between a photograph of an actual object and a photograph of the hologram of the object. However, as the field progresses and the quality of images increases, this discrimination becomes increasingly difficult. Various hologram images we present here, particularly those recorded recently using the technique of full-colour analogue holography, may therefore appear to simply be photographs—which, of course, is not the case!

H. I. Bjelkhagen
D. Brotherton-Ratcliffe
London, UK

Acknowledgments

This book would not have materialised without the inspiration and encouragement of many people. Various people and institutions have also helped in providing material, which has made the book more interesting and more complete. First and foremost, we would both like to thank John Navas of Taylor & Francis, CRC Press for his encouragement and support in writing this book. Thanks also to Rachel Holt and Amber Donley of Taylor & Francis.

DBR: I would like to especially thank Nicholas Phillips, even though, sadly Nick is no longer with us, for the interesting and penetrating discussions I had with him, for his never-waning enthusiasm, and most importantly for his amazing inspiration: it was Nick's work that inspired me to take up holography in the first place. I would also like to say a special thank you to Stanislovas Zacharovas for his continual support with Geola over the years. I would like to thank Mikhail Grichine and Alexej Rodin for their part in introducing me to pulsed laser photonics and for many years of invaluable discussions; thanks also to Marcin Lesniewski for his vitally important input in the area of high numerical aperture Fourier transform objective design. I would like to thank Ramunas Bakanas for our long discussions on all aspects of laser physics and on the optics of digital holographic printers—and also for his unwavering commitment to Geola. I would like to thank Lev Isacenkov, without whom the Geola organisation would never have existed, and Eric Bosco and Lynne Hrynkiw, the founders of XYZ Imaging Inc., for their constant enthusiasm and great contribution to the practical realisation of direct-write digital holography. Thanks also to Yuri Sazonov and Olga Gradova, without whom Geola's work in digital holography would not have gotten very far, through lack of a suitable photosensitive film. Many thanks also to Paula Dawson, Juyong Lee and Jesper Munch for their support, first of Australian Holographics Pty. Ltd., and then of the Geola organisation. I should also mention Peter Hering from the Caesar Institute and Rob Taylor of Forth Dimension Holographics Inc. I would like to thank Andrej Nikolskij, Julius Pileckas and Jevgenij Kuchin at Geola, not only for their help in checking my formulae in Chapters 8 and 9, but also for their commitment over the years to Geola. Thanks also to John Fleming, who worked with me on the design project that led to Appendix 6, and to Chris Chatwin and Rupert Young for our fruitful collaborations at the University of Sussex. Finally, I would like to thank key members of the teams at Australian Holographics Pty. Ltd., LMC France Instruments SARL, Geola Technologies Ltd. (GT) and at the Centre for Laser Photonics (CLP) in North Wales—Geoff Fox (AH), Svetlana Karaganov (AH), Simon Edhouse (AH), Yasmin Farquhar (AH), Vytas Serelis (AH), Florian Vergnes (LMC and later manager of Geola UAB), Jerzy Lelusz (GT/CLP), Nataly Vidmer (GT/CLP), Lishen Shi (GT/CLP), Junhua Lu (GT) and John Tapsell (GT).

HB: I would like to thank Nils Abramson at the Royal Institute of Technology in Stockholm, who introduced me to holography in 1968 and who was responsible for my decision to select holography as a professional career. My Swedish colleagues, Per Skande and Johnny Gustafsson were involved in many of the commercial display holography projects carried out at Holovision AB in the 1970s. I would also like to express my gratitude to Tung H. Jeong, Lake Forest College, Illinois, for his collaboration in several projects including the *Lake Forest International Display Holography Symposia* with which I have been involved since 1982. Ed Wesly, from Chicago, has collaborated in many of my projects, both at Fermilab, Northwestern University, and holography business activities in Chicago. Thanks also to Max Epstein and Michel Marhic, Northwestern University, who were involved in many of the research projects carried out when I was working at the University in Evanston as well as being my colleagues at Holicon Corp. and the Light Wave hologram galleries in the United States. I am particularly thankful to Nicholas Phillips who invited me in 1997 to join him at the Centre for Modern Optics (CMO) at De Montfort University in Leicester, UK. Together, we worked on improving silver halide materials and processing methods, even after CMO moved to Wales. In particular, Nick had a lot of input into the European *SilverCross* emulsion project. Ardie Osanlou, my long-time CMO colleague, is gratefully acknowledged for working with me on many of our holography projects. Peter Crosby and Evangelos Mirlis, one of my PhD students, have both been particularly helpful in the emulsion and museum holography projects. In regard to my Lippmann photography research, I must acknowledge Darran Green's important contribution. Since the 1990s, one of my main interests in holography has been to develop ultra-realistic 3D images, which required recording high-quality colour holograms, in particular, of the Denisyuk single-beam reflection type. My very first such experiments were carried out in France together with Dalibor Vukičević, Strasbourg University, who devoted a lot of his time helping to record the first successful results. I had the honour to know and meet both Emmett Leith and Yuri Denisyuk many times. I am very thankful for the many valuable discussions I had with them and for the support they gave me in my research on holographic recording materials and display holography applications. I want to also mention Gennady and Svetlana Sobolev, Michael Shevtsov and Vladimir Markov, who for many years, have been very helpful, providing me with insights into ultrafine-grain silver halide emulsions. In addition, I would like to mention my Bulgarian colleague and friend, Ventseslav Sainov, who has worked with me on emulsions and colour holography projects. Last but not least, I would like to express my deep gratitude to Teresa Bjelkhagen, who provided me with translations of important Russian publications such as N. I. Kirillov's 1979 book on ultrahigh-resolution emulsions. She has also supported my work in holography from the beginning.

Authors

Dr Hans I. Bjelkhagen, Professor Emeritus of Interferential Imaging Sciences at Glyndŵr University, Centre for Modern Optics (CMO), located in North Wales, UK, was awarded his Doctoral Degree in 1978 by the Royal Institute of Technology in Stockholm, Sweden.

Over the last 15 years, Bjelkhagen has received much international recognition for his work in the field of colour holography and holographic recording materials. He has specialised in recording Denisyuk-type colour holograms. He has also researched and improved Lippmann photography over a period of many years.

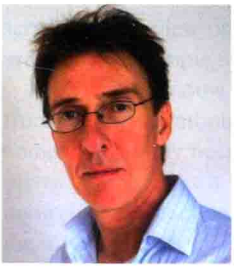
In 1983, Bjelkhagen joined CERN in Geneva, Switzerland, where he was involved in the development of bubble chamber holography. A year later, he participated in an international team project, recording holograms in the 15-foot bubble chamber at Fermilab in Batavia, Illinois. Between 1985 and 1991, he was employed at Northwestern University, in Illinois, working on medical applications of holography.

In 1997, Bjelkhagen was invited by Professor Nick Phillips to join him at CMO at De Montfort University, Leicester, England. In 2004, CMO moved to the then newly established OpTIC in Wales.

In addition to scientific applications, Bjelkhagen is a well-known holographer who has recorded many holograms for 3D display purposes. From his early years in the field, he has been involved in large-format, high-quality display holography, using both pulsed and CW lasers. He has recorded many unique art objects, such as the Swedish *Coronation Crown of Erik XIV* (the crown dates back to 1561), and the Chinese *Flying Horse from Kansu* (from 100 AD). Bjelkhagen has worked with a number of famous artists, for example, Carl Fredrik Reuterswärd, creating holograms exhibited in many art museums and galleries around the world.

Bjelkhagen has also used pulsed holography to record a number of holographic portraits. In 1989, he recorded a portrait of the inventor of single-beam reflection holography, Yuri Denisyuk. The most famous person recorded by Bjelkhagen was President Ronald Reagan. His portrait was recorded on 24 May 1991. This was the first and, so far, the only holographic portrait recorded of an American President. A copy of this holographic portrait is held in The National Portrait Gallery of the Smithsonian Institution in Washington, DC.

Bjelkhagen has published more than 100 papers in refereed journals and conference proceedings, and holds 14 international patents. His most important academic contribution is a book on *Silver-Halide Recording Materials for Holography and Their Processing* published by Springer. He is a member of the Optical Society of America and is a fellow of the International Society for Optical Engineering (SPIE). He is the Chairman of SPIE's Photonics West Practical Holography Conference and SPIE's Holography Technical Group. He is an Accredited Senior Imaging Scientist and Fellow of the Royal Photographic Society (RPS) as well as Chairman of the RPS 3D Imaging & Holography Group. In 2001, he received the RPS Saxby Award for his work in holography, and in 2011, the Denisyuk Medal, from the D.S. Rozhdestvensky Optical Society, Russia.



Dr David Brotherton-Ratcliffe is the founder and scientific director of the well-known laser physics and holography organisation, Geola. He obtained a BSc (Hons) in Physics and Astrophysics from Queen Mary College, London University, in 1981. In 1984, while still at London University but now seconded to the United Kingdom Atomic Energy Authority at Culham Laboratories, he received a PhD for his work in nuclear fusion and magnetohydrodynamics. From 1985 to 1989, he continued to work as a theoretical physicist at the Flinders University of South Australia.

Brotherton-Ratcliffe first started to work in holography in 1982 during his doctoral studies, but it was not until 1989 that he founded Australian Holographics Pty. Ltd. and began working full-time in the fields of holography, optics and laser physics. During the 1990s, Australian Holographics became well known for its large-format display holograms, which were successfully marketed in Australia and throughout the Asia-Pacific region, often attracting significant media coverage.

In 1992, Brotherton-Ratcliffe founded the Geola organisation in Lithuania and began working seriously on high-energy pulsed laser technology. He founded associated companies in Australia, France and Romania, and travelled frequently between these countries for several years.

In 1999, Brotherton-Ratcliffe patented a key idea that proved to be highly influential: the printing of full-colour digital holograms, dot by dot, using RGB pulsed lasers. Over the years since 1999, Brotherton-Ratcliffe has come to be recognised as one of the leading workers in the expanding field of digital holographic printing.

Brotherton-Ratcliffe is the author of more than 14 patent families and over 60 publications in refereed journals and conference proceedings. He has published in the fields of plasma physics, magnetohydrodynamics, nuclear fusion, theoretical physics, laser physics, optics, holography and aerodynamics.

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