Interacting with augmented holograms

Oliver Bimber[*], Thomas Zeidler, Anselm Grundhoefer, Gordon Wetzstein,
Mathias Moehring, Sebastian Knoedel, and Uwe Hahne
Bauhaus-University Weimar, Media Faculty, Bauhausstr. 11, 99423 Weimar, Germany

ABSTRACT

Holography and computer graphics are being used as tools to solve individual research, engineering, and presentation problems within several domains. Up until today, however, these tools have been applied separately. Our intention is to combine both technologies to create a powerful tool for science, industry and education. We are currently investigating the possibility of integrating computer generated graphics and holograms.

This paper gives an overview over our latest results. It presents several applications of interaction techniques to graphically enhanced holograms and gives a first glance on a novel method that reconstructs depth from optical holograms.

Keywords: Computer Graphics, Human-Computer Interaction, Projection Technology, Real-Time Rendering, Augmented Holograms, Depth Reconstruction.

1. INTRODUCTION

Among all imaging techniques that have been invented throughout the last decades, computer graphics is one of the most successful tools today. Many areas in science, entertainment, education, and engineering would be unimaginable without the aid of 2D or 3D computer graphics. The reason for this success story might be its interactivity, which is an important property that is still not provided efficiently by competing technologies – such as holography.

While optical holography and digital holography are limited to presenting a non-interactive content, electroholography facilitates the computer-based generation and display of holograms at interactive rates[2,3,29]. Holographic fringes can be computed by either rendering multiple perspective images, then combining them into a stereogram[4], or simulating the optical interference and calculating the interference pattern[5]. Once computed, such a system dynamically visualizes the fringes with a holographic display. Since creating an electrohologram requires processing, transmitting, and storing a massive amount of data, today's computer technology still sets the limits for electroholography. To overcome some of these performance issues, advanced reduction and compression methods have been developed that create truly interactive electroholograms. Unfortunately, most of these holograms are relatively small, low resolution, and cover only a small color spectrum. However, recent advances in consumer graphics hardware may reveal potential acceleration possibilities that can overcome these limitations[6].

In parallel to the development of computer graphics and despite their non-interactivity, optical and digital holography have created new fields, including interferometry, copy protection, data storage, holographic optical elements, and display holograms. Especially display holography has conquered several application domains. Museum exhibits often use optical holograms because they can present 3D objects with almost no loss in visual quality. In contrast to stereoscopic or autostereoscopic graphics displays, holographic images can provide all depth cues—perspective, binocular disparity, motion parallax, convergence, and accommodation—and theoretically can be viewed simultaneously from an unlimited number of positions. Displaying artifacts virtually removes the need to build physical replicas of the original objects. In addition, optical holograms can be used to make engineering, medical, dental, archaeological, and other recordings—for teaching, training, experimentation and documentation. Archaeologists, for example, use optical holograms to archive and investigate ancient artifacts[7,8]. Scientists can use hologram copies to perform their research without having access to the original artifacts or settling for inaccurate replicas.

[*] bimber@uni-weimar.de; phone +49-(0)3643-583724; fax +49-(0)3643-583724; www.uni-weimar.de/medien/AR;
www.holographics.de (**high-resolution color versions of images presented in this paper are available online**)

Optical holograms can store a massive amount of information on a thin holographic emulsion. This technology can record and reconstruct a 3D scene with almost no loss in quality. Natural color holographic silver halide emulsion with grain sizes of 8 *nm* is today's state-of-the-art[14].

Today, computer graphics and raster displays offer a megapixel resolution and the interactive rendering of megabytes of data. Optical holograms, however, provide a terapixel resolution and are able to present an information content in the range of terabytes in real-time. Both are dimensions that will not be reached by computer graphics and conventional displays within the next years – even if Moore's law proves to hold in future.

Obviously, one has to make a decision between interactivity and quality when choosing a display technology for a particular application. While some applications require high visual realism and real-time presentation (that cannot be provided by computer graphics), others depend on user interaction (which is not possible with optical and digital holograms). Consequently, holography and computer graphics are being used as tools to solve individual research, engineering, and presentation problems within several domains. Up until today, however, these tools have been applied separately. Our intention is to combine both technologies to create a powerful tool for science, industry and education.

We are currently investigating the possibility of integrating computer generated graphics and holograms[1]. Our goal is to combine the advantages of conventional holograms (i.e. extremely high visual quality and realism, support for all depth queues and for multiple observers at no computational cost, space efficiency, etc.) with the advantages of today's computer graphics capabilities (i.e. interactivity, real-time rendering, simulation and animation, stereoscopic and autostereoscopic presentation, etc.).

The remainder of this paper is organized as follows: Chapter 2 briefly summarizes the general concept of digitizing the reconstruction wave to reply a hologram. Spatial distribution, amplitude and wavelength can be controlled to augment holograms consistently with graphical elements. Since depth information of both –holographic and graphical content– is essential for our approach, chapter 3 presents our initial results of using a flat bed scanner for estimating holographic depth information. Chapter 4 discusses several interaction forms in combination with different hologram types and describes current experimental display configurations. It is shown how the viewing range of augmented holograms can be increased with the aid of multiplex stereograms and how augmented holograms can be embedded into windows-oriented desktop workplaces. Furthermore, we demonstrated how force-feedback and touch-interaction can be applied to augmented holograms, and how to combine volumetric multiplexed holograms with stereoscopic graphics. Finally, chapter 5 concludes our contribution and identifies some limitations and future directions.

2. DIGITAL LIGHT FOR RECONSTRUCTING HOLOGRAMS

The two basic hologram types—transmission and reflection—are both reconstructed by illuminating them with spatially coherent light (i.e. using a point-source of light). These two types have generated a number of variations. Although some holograms can be reconstructed only with laser light, others can be viewed under white light.

Conventional video projectors represent point sources that are well suited for viewing white-light reflection or transmission holograms. Early experiments with video projectors for reconstructing optical holograms have been made in the art and engineering domains. In some art installations, optical holograms have been linked with time-based media, such as slides, film-loops or color effects that are projected onto them to achieve artistic effects[15, 16]. Others have redirected projected light with multiple mirrors to simulate multiple different light sources. The goal was to achieve dynamic fluctuation effects with optical holograms[17,18].

Today's high-intensity discharge lamps of projectors can produce a very bright light. The main advantage for using video projectors instead of analog light bulbs is that the reference wave used to reconstruct the hologram can be digitized. Thus it is possible to control the amplitude and wavelength of each discrete portion of the wavefront over time[1]. Today's computer graphics capabilities allow merging any kind of two-dimensional or three-dimensional graphical elements seamlessly with the recorded holographic content – potentially leading to efficient visualization tools that combine the advantages of holography and computer graphics.

A hybrid display approach has already been described earlier that combined a transmission hologram with a liquid crystal display to realize a new user interface for business machines, such as photocopiers[19]. In this case, a normal light bulb was used to illuminate a transmission hologram which was mounted behind an LCD panel. Since the light source was analog, it was not possible to control the reconstruction of the holographic content. Electronically activated two-dimensional icons that were displayed on the LCD appeared simultaneously and unregistered with the three-dimensional hologram. As mentioned above, video projectors allow digitizing the reference wave, which leads to a seamless integration of graphical elements into an optical hologram.

Figure 1 shows the projected reference wave (top row) in different states, and the resulting holographic image (bottom row) of a monochrome white-light reflection hologram. A uniform reference wave reconstructs the entire hologram uniformly (first column of fig. 1). Selectively emitting light in different directions allows us to create an incomplete reference wave that reconstructs the hologram only partially (second column of fig. 1). Local amplitude variations in the reference wave result in proportional amplitude variations in the reconstructed object wave (third column of fig. 1). Variations in wavelength do not lead to useful effects in most cases due to the wavelength dependency of holograms (fourth column of fig. 1). But this is still a matter for further investigations. One example for encoding color information into the reference wave is described in section 4.6.

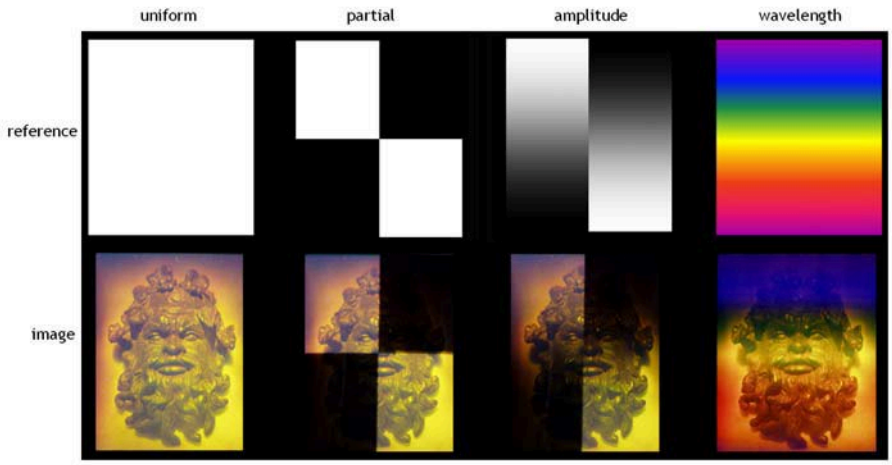

Figure 1: The projected reference waves (top row) and the resulting holographic images (bottom row).

The following sub-sections will give only a brief overview of the possibilities of using a digitized reference wave for reconstructing optical holograms. The interested reader is referred to the primary publication[1] for details on rendering and illumination techniques.

2.1. Partially reconstructing object waves

It is possible to reconstruct the object wave of a hologram only partially, leaving gaps where graphical elements can be inserted. Both reflection holograms (without an opaque backing layer) and transmission holograms remain transparent if not illuminated. Thus, they can serve as optical combiners—leading to very compact displays. Real-time computer graphics can be integrated into the hologram from one side, while illuminating it partially from the other side[1].

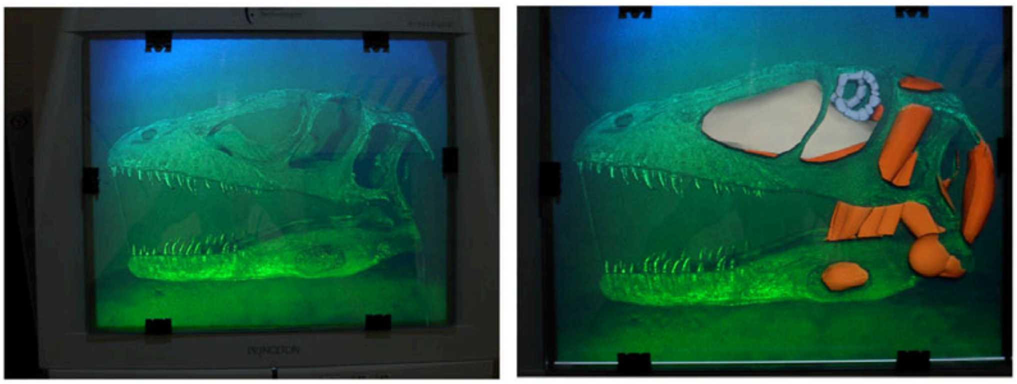

Figure 2: Rainbow hologram of a dinosaur skull combined with graphical representations of soft tissue and bones.

Thereby, rendering and illumination are view-dependent and have to be synchronized. If autostereoscopic displays are used to render 3D graphics registered to the hologram, both holographic and graphical content appear three-dimensional

within the same space. If depth information of both is known, correct occlusion effects between hologram and graphics can be generated. One possible approach of acquiring depth information directly from a white-light hologram is explained in chapter 3.
Figure 2 shows a rainbow hologram of a dinosaur skull combined with graphical representations of soft tissue and bones. If the holographic plate is illuminated with a uniform light, the entire hologram is reconstructed (fig. 2-left). If the plate is illuminated only at the portions not occluded by graphical elements, the synthetic objects can be integrated by displaying them on the screen behind the plate (fig. 2-right). Technical details on how this is achieved will be presented in section 4.1.

2.2. Light interaction

The reconstructed object wave's amplitude is proportional to the reference wave's intensity. In addition to using an incomplete reference wave for reconstructing a fraction of the hologram, intensity variations of the projected light permit local modification of the recorded object wave's amplitude.
Practically, this means that to create the illumination image which is sent out by the projector, graphical shading and shadowing techniques are used to reconstruct the hologram instead of illuminating it with a uniform intensity. To do this, the real shading effects on the captured scenery caused by the real light sources used for illumination during hologram recording, as well as the physical lighting effects caused by the video projector on the holographic plate, must both be neutralized. Next, the influence of a synthetic illumination must be simulated[1].
Using conventional graphics hardware, it becomes possible not only to create consistent shading effects, but also to cast synthetic shadows correctly from all holographic and graphical elements onto all other elements.

Figure 3: A rainbow hologram with 3D graphical elements and synthetic shading and shadow effects.

Figure 3 shows the same rainbow hologram as above with 3D graphical elements and synthetic shading effects. Shadows are cast correctly from the hologram onto the graphics and vice versa. A virtual point-source of light was first located at the top-left corner (L_1 in fig. 3-left), and then moved to the top-right corner (L_2 in fig. 3-right), in front of the display. Moving the virtual light source and computing new shading effects can be done in real-time. Note, that only intensity/shading variations are simulated in figure 3. A vertical variation of the object wave's wavelength that is due to diffraction effects of the rainbow hologram is still visible and cannot be corrected. This is not the case for white-light reflection holograms.

3. RECONSTRUCTING HOLOGRAPHIC DEPTH WITH FLATBED SCANNERS

Depth information of the recorded holographic content is essential for correct rendering and interaction in combination with augmented graphical elements. The shading and occlusion effects that are presented in sections 2.1 and 2.2, as well as the force-feedback simulation that is discussed in section 4.4 would not be possible without knowing the surface geometry of the holographic content. For demonstrating the capabilities of the various techniques, the object's surface geometry has been laser-scanned before recording it as a hologram. The scanned geometric model is then registered to its holographic counterpart during a pre-process. This allows computing estimated depth values of the surfaces recorded

in the hologram. However, since the original objects are usually not available for scanning after the recording process, the depth information has to be extracted directly out of the hologram.
Ultra-fast holographic cameras, for instance, have been modified to allow capturing 3D objects, such as faces[20] or bodies[21]. A fast pulsed laser with short exposure time (25*ns*) is used in these cases for holographic recording that is free of motion artifacts. The depth information is then reconstructed by illuminating the hologram with a laser. Topometric information is retrieved by digitizing the real holographic image that is projected onto a diffuse plate. Moving the plate in the depth direction (away from the holographic plate) results in several 2D slices through the holographic image. These slices are finally combined to form the corresponding 3D surface.
Another approach measures the shape of a recorded surface by determining the time for light to travel from different points of the object[22]. They are based on the holographic light-in-flight technique[23].
The sections below describe our initial results of a new approach that uses a flat bed scanner for estimating holographic depth information.

3.1 Scanning Multiple Views

Two commercial types of flatbed scanners exist today: Most scanners apply a CCD (charge-coupled device) array that captures a parallel projected image in the moving direction of the scanning slit and a perspective projected image in the other direction. A new optical technology has been introduced by Canon –called LIDE (LED InDirect Exposure)– to reduce the size of scanners. An array of parallel rod lenses over the entire scanner width creates a parallel projection in both directions. Thus, a LIDE scanner represents a parallel perspective camera with a low focal depth.

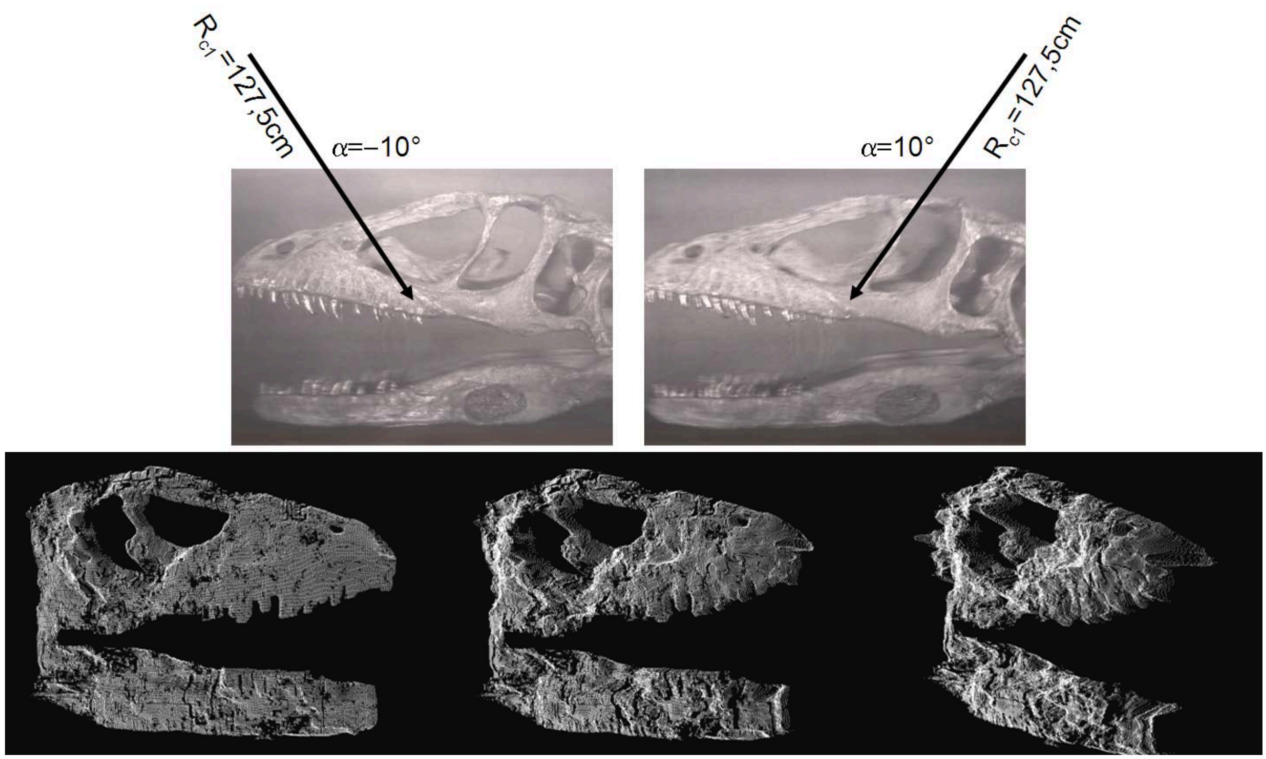

Figure 4: Two LIDE scans of a rainbow hologram with different reference wave angles (top), and point-cloud of reconstructed depth map (bottom).

We use the LIDE technology to scan multiple images of a hologram by placing the holographic film on top of the scanner window, leaving the lit open and illuminating it under different illumination angles for each scan (cf. figure 4). The geometric image distortion that is caused by the different illuminations[26] is captured with a parallel camera model defined by the scanner. In this case, an analytical solution exists for computing depth information if the correspondences between 2D image projections (disparities) are known.

3.2 Computing 2D Disparities

Common 3D scanning techniques analyze images that are taken from cameras located on the same base-line by searching for pixel correspondences along a single direction. Due to the complex warping behavior of holograms when they are illuminated under different situations[26] our method requires to compute 2D disparities. We apply an algorithm that uses a hierarchical stereo matching strategy using the discrete wavelet transform (DWT)[28]. As mentioned above, the hologram is reconstructed from at least two different (but known) light positions. Images of the hologram are scanned with a LIDE flatbed scanner while being illuminated from these positions. If the correspondences between a minimum of two images are known it is possible to estimate depth values. More images that are recorded under additional light positions can add redundancy and consequently enhance the outcome. However, the cross-correspondence between single image pairs has still to be computed. Thus we only describe the analytical solution for the basic case of computing depth from two parallel perspective images.

3.3 Estimating Depth

With the computed disparities we aim at estimating the depth z_o of all visible pixels. The geometric imaging behavior of holograms under different lighting conditions has been well understood[26]. Based on this model, a numerical method has been derived that estimates the image position of recorded objects for cases in which the recording reference beam does not match the reply reference beam, and a known perspective viewing situation is assumed[27]. This is illustrated in figure 5.

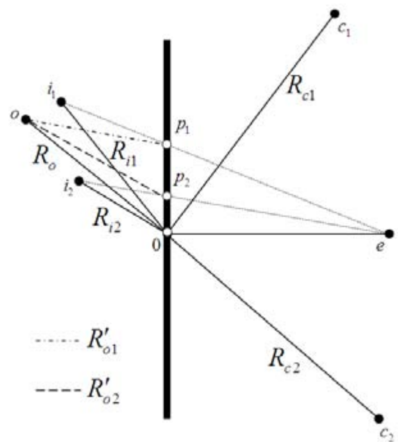

Figure 5: Flatland diagram of reconstruction geometry.

Since the LIDE scanner provides a parallel projection in both directions, an analytical solution can be found. For a parallel projection, the viewpoint e can be assumed to be located at infinity. Because of this the principal ray points p_i are known for both lighting positions c_1 and c_2: $x_p = x_i$ and $y_p = y_i$. Thus, the reconstructed image points i_i of a recorded object o and the position of the viewer e are collinear. With these two constraints the equation that can be derived for the perspective case[27] reduces to:

$$0 = \frac{x_c - x_i}{R'_c} + \mu\left(\frac{x_0 - x_i}{R'_o} - \frac{x_r - x_i}{R'_r}\right) \tag{1}$$

This also holds for the other dimension:

$$0 = \frac{y_c - y_i}{R'_c} + \mu\left(\frac{y_0 - y_i}{R'_o} - \frac{y_r - y_i}{R'_r}\right) \tag{2}$$

Note, that $\mu = \lambda_c / \lambda_r$ where λ_c is the reconstruction wavelength and λ_r is the recording wavelength. This ratio can vary slightly from the theoretical value due to changes in humidity during reconstruction. Note also, that the radii R

are measured from the origin 0 while the radii R' are measured from the corresponding principle ray points p_i. The origin and the principle ray points lie on the holographic plane. Equations (1) and (2) are valid for all light positions. Solving these equations for x_0 and y_0 we receive:

$$x_0 = R'_{o1}\underbrace{\left(\frac{x_r - x_{i1}}{R'_{r1}} - \frac{x_{c1} - x_{i1}}{\mu R'_{c1}}\right)}_{a} + \mathrm{x}_{i1} \text{ and } x_0 = R'_{o2}\underbrace{\left(\frac{x_r - x_{i2}}{R'_{r2}} - \frac{x_{c2} - x_{i2}}{\mu R'_{c2}}\right)}_{b} + x_{i2} \tag{3}$$

$$y_0 = R'_{o1}\underbrace{\left(\frac{y_r - y_{i1}}{R'_{r1}} - \frac{y_{c1} - y_{i1}}{\mu R'_{c1}}\right)}_{c} + \mathrm{y}_{i1} \text{ and } y_0 = R'_{o2}\underbrace{\left(\frac{y_r - y_{i2}}{R'_{r2}} - \frac{y_{c2} - y_{i2}}{\mu R'_{c2}}\right)}_{d} + y_{i2} \tag{4}$$

From equation (3) follows:

$$R'_{o1} = \frac{bR'_{o2} + x_{i2} - x_{i1}}{a} \tag{5}$$

Equation (4) yields:

$$R'_{o1} = \frac{dR'_{o2} + y_{i2} - y_{i1}}{c} \tag{6}$$

With equations (5) and (6) R'_{o2} can be calculated, and with known R'_{o2} the depth for every projected object o is:

$$z_o = R'_{o2}\sqrt{1 - \frac{(x_o - x_{i2})^2}{R'^2_{o2}} - \frac{(y_o - y_{i2})^2}{R'^2_{o2}}} \tag{7}$$

Note, that correct disparities (which define the correspondences between the two images i_1 and i_2) are essential for computing the correct depth values. This still represents our main challenge.

4. ADDING INTERACTIVITY

We believe that interactivity is one of the success factors of modern computer graphics. Electroholography has a great potential to provide truly interactive holograms. However, several technological hurdles have to be taken before this will become a real competitor to computer graphics. Combining holograms and interactive computer graphics represents an intermediate solution that can be achieved today with off-the-shelf equipment. The following sections describe current experimental display prototypes and present several interaction forms in combination with different hologram types.

4.1 Display prototypes

Figure 6 shows two desktop prototypes. They serve as proof-of-concept configurations and as testbeds for experiments. The stereoscopic version (figure 6-left) consists of a conventional CRT screen with active stereo glasses, wireless infrared tracking, and a touch screen in front of the hologram for interaction. The autostereoscopic version uses an autostereoscopic lenticular-lens sheet display with integrated head-finder for wireless user tracking and a force feedback device[9] for six degrees-of-freedom interaction.

For the autostereoscopic display prototype, a digital light projector (DLP) is applied for illuminating the hologram. Since the DLPs' time-multiplexed generation of light intensities causes synchronization conflicts with the shuttering of the active LC glasses, an LCD projector is used for the stereoscopic version instead.

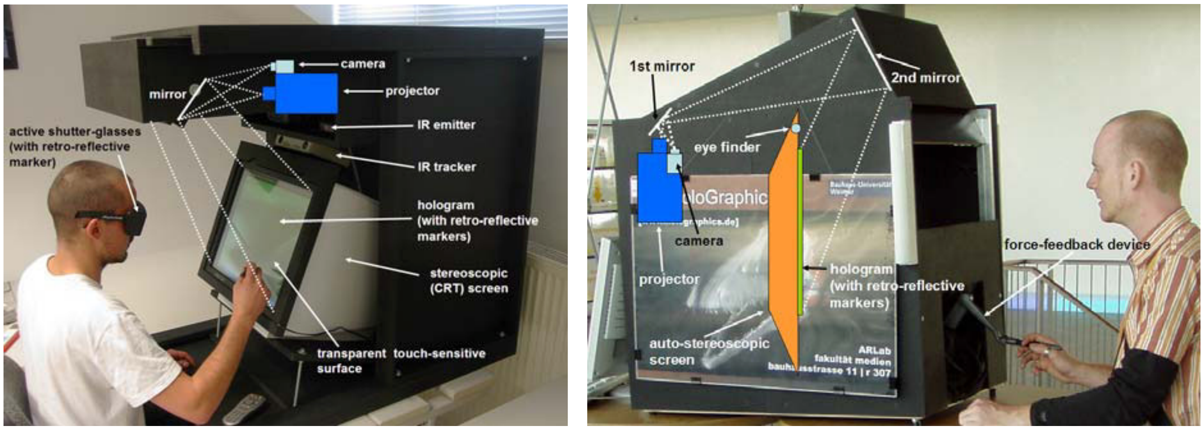

Figure 6: Stereoscopic (left) and autostereoscopic (right) display prototypes.

A single PC with a dual-output graphics card renders the graphical content on the screen and the illumination for the holographic plate on the video projector. In both cases, the screen additionally holds further front layers (cf. figure 7) – glass protection, holographic emulsion, and optional mirror beam combiner (used for transmission holograms only).

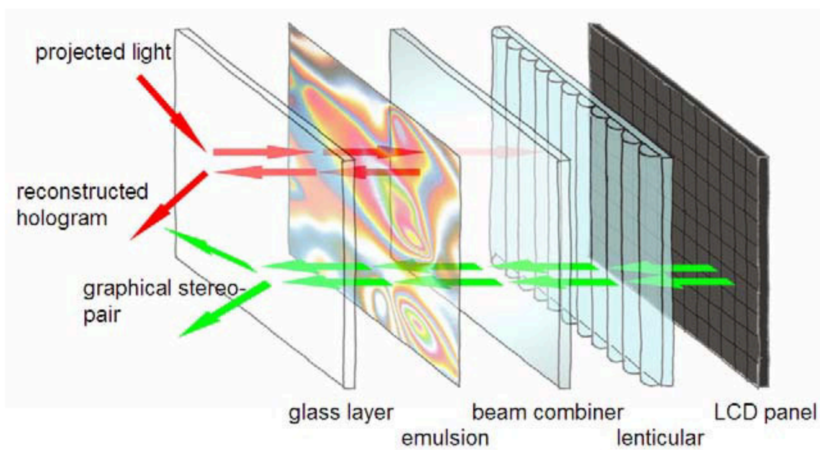

Figure 7: Explosion model of the optical layers' stacked structure. The example shows a transmission hologram in combination with autostereoscopic lenticular screen.

Interaction with the graphical content is supported with a mouse, a touch-sensitive transparent screen mounted in front of the holographic plate, or a 6DOF force feedback device (see section 4.4).

In addition, a camera is mounted close to the projector to detect reto-reflective markers that are attached to the holographic plate. Using structured light probes ensures a fully automatic registration of the holographic plate and calibration of the projector.

4.2 Increasing viewing range with multiplex stereograms

Digital holography uses holographic printers to expose the photometric emulsion with computer-generated or captured images. This results in conventional holograms with digital content rather than real scenery. Pre-processed 2D and 3D graphics or digital photographs and movies can be printed. This allows to holograph, for instance, completely synthetic objects, real outdoor sceneries, and objects in motion - which is difficult and sometimes impossible to achieve with optical holography. Like optical holograms, digital holograms can be multiplexed. This allows to divide the viewing space and to assign individual portions to different contents. The content for digital holograms can easily be created by non-experts, and the printing process is inexpensive. Usually a 3D graphical scene, a series of digital photographs or a short movie of a real object is sufficient for producing digital holograms. But digital holograms lack in the quality (resolution, color appearance, sharpness, etc.) of optical holograms.

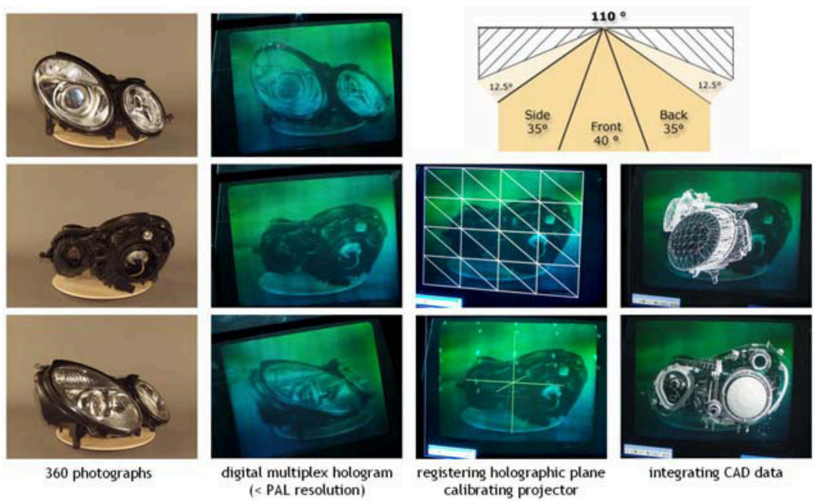

Figure 8: A multiplexed digital reflection stereogram of a car headlight with integrated CAD data.

Figure 8 shows a digital color white-light reflection stereogram of a car's head-light. It was generated by taking 360 perspective photographs from different angles (in 0.5 degree steps to cover a 110° total viewing zone plus two 35° deg clipping areas). The perspective photographs were multiplexed into different sub-zones (40°=80 images for the front view + 2x35°=140 images for the side and rear views + 2x12.5°=50 images to fill the partially visible clipping area outside the 110° total viewing zone + 2x22.5°=90 images to fill the invisible clipping area outside the 110° total viewing zone). Consequently, three different partial views (front, rear, and side) can be observed by moving within the total viewing zone of 110°. After registering the holographic plane and calibrating the projector, interactive graphical elements, such as wire-frame or shaded CAD data can be integrated into the hologram. Since the head motion of the observer is tracked and the recorded viewing angles are known, the perspective of the graphical content can be updated to match the corresponding perspective recorded in the hologram. Thus, graphical and holographic content remain registered – regardless of the observer's viewing direction. This supports a non-continuous surround view of recorded and augmented scenes.

4.3 Holographic windows

The ability to digitally control the reconstruction of a hologram allows integrating them seamlessly into common desktop-window environments. If the holographic emulsion that is mounted in front of a screen is not illuminated, it remains transparent. In this case the entire screen content is visible and an interaction with software applications on the desktop is possible in a familiar way. The holographic content (visible or not) is always located at a fixed spatial position within the screen/desktop reference frame. An application that renders the graphical content does not necessarily need to be displayed in a full screen mode (as in the examples above), but can run in a windows mode - covering an arbitrary area on the desktop behind the emulsion. If position and dimensions of the graphics window are known, the projector-based illumination can be synchronized to bind the projected light to the portion of the emulsion that is located directly on top of the underlying window.

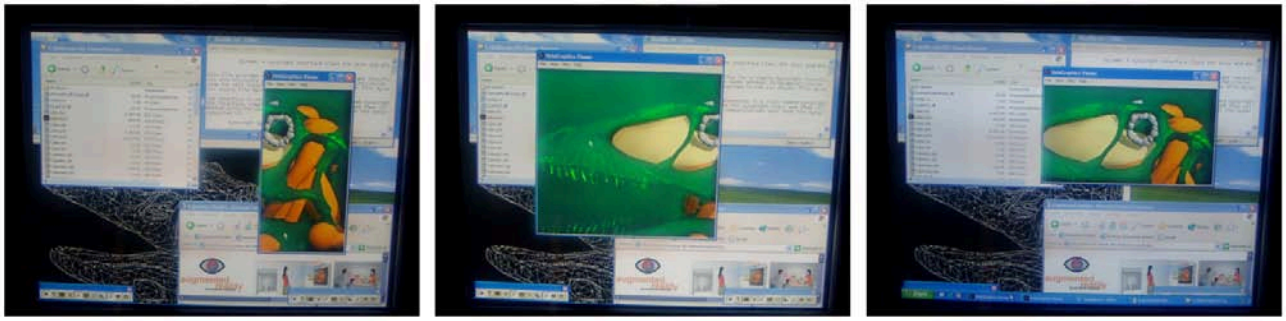

Figure 9: A holographic window in different states on a desktop together with other applications. The hologram is a white-light reflection hologram.

Thereby, all the techniques that are described in section 2 (partial reconstruction and intensity variations) are constrained to the window's boundaries. The remaining portion of the desktop is not influenced by the illumination, the graphical or the holographic content. In addition, the graphical content can be rendered in such a way that it remains registered with the holographic content - even if the graphical window is moved or resized. This simple, but effective technique allows a seamless integration of holograms into common desktop environments. It allows to temporarily minimize the "holographic window" or to align it over the main focus while working with other applications. Figure 9 shows a holographic window in different states on a desktop together with other applications. It displays an optical (monochrome) white-light reflection hologram of a dinosaur skull with integrated graphical 3D soft tissues. A stereoscopic screen was used in this case, because autostereoscopic displays (such as lenticular screens or barrier displays) do not yet allow an undisturbed view on a non-interlaced 2D content (such as text with a small font).

4.4 Force-feedback interaction

Haptic interaction devices, such as Massie's PHANTOM[9], allow to feel computer generated 3D content by simulating force feedback. Depending on the position of the 6DOF stylus-like device (cf. figures 6-right and 10), force vectors and magnitudes are calculated dynamically based on pre-defined material parameters of the corresponding holographic or graphical content. This enables the user to virtually touch and feel the hologram and the integrated virtual models. For both content types a 3D geometrical model is required to determine surface intersections with the stylus, which lead to the proper force computations. The device is installed outside the user's viewing volume and allows controlling a 3D cursor remotely. This prevents from occluding parts of the screen or casting shadows from the projected light.

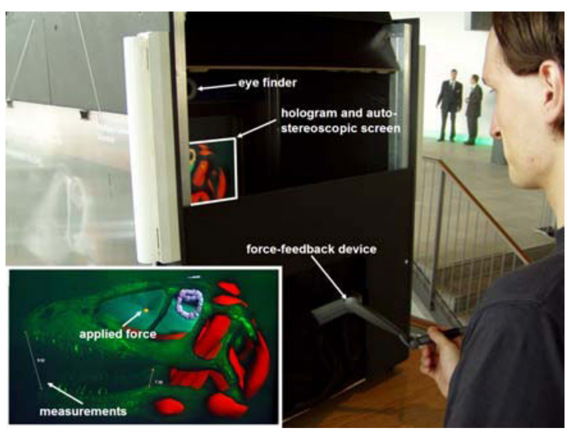

Figure 10: Force-feedback interaction with a reflection hologram of a dinosaur skull and augmented graphical soft-tissue.

While the holographic content is static, the graphical content can be deformed by the device in real time. As in some of the previous examples, a reflection hologram of a dinosaur skull has been augmented with reconstructed soft tissue. Using the force feedback device allows touching and feeling bones and muscles with different material parameters.

While bones feel stiff, muscles and air sinus feel differently soft. In addition, the soft tissue can be pushed in under increasing pressure, and expand back when released. Furthermore, measurements of distances can be taken by touching arbitrary points in space with a virtual measuring tool that is controlled by the stylus.
Other groups have experimented force feedback interaction in combination with static reflection transfer holograms[10], edge-illuminated holograms[11], and dynamic electroholograms[12,13]. Note, that in contrast to electroholograms, optical holograms are static. A modification of the holographic content is not possible in this case. This is also true for our approach. Only the graphical content can be dynamically modified. However, force feedback can be simulated for both - the holographic and the graphical part.

4.5 Touch interaction

A transparent and touch-sensitive surface can be used as front layer to support touch and pointing interactions. The prototype illustrated in figure 11 applies a resistive analog touch screen with an invisible spacer, a touch resolution of 2048x2048 on a surface of 30x40*cm*, an 80% nominal light transmission, 10*ms* responds time and a maximum error of 3*mm*. Touch events are activated through pressure – by finger, fingernail, gloved hand or stylus. The resulting 2D position of the pointer on the registered panel in combination with the head-position of the observer (known from head-tracking) leads to a 3D ray that can be used by ray-casting techniques to select holographic or graphical objects that are intersected by the ray.

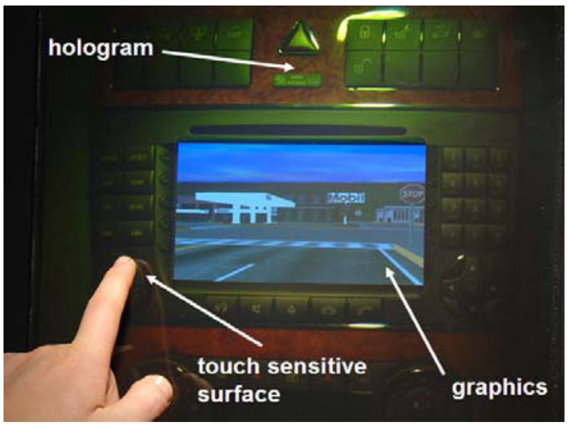

Figure 11: A full color hologram of a car navigation console. Graphics is integrated into the console's display to simulate the design of novel graphics interfaces before building prototypes.

In the example shown in figure 11, touch interaction is used for operating the recorded keypad of a car navigation system. A high-quality full color Denisjuk hologram replays the console while monoscopic or autostereoscopic graphics is integrated into the console's original LCD panel. This allows simulating novel 2D/3D graphics interface designs, as well as new interaction and presentation schemes for navigation systems under realistic evaluation conditions before building physical prototypes. Touching the surface above a recorded button triggers the specific function of the system and the augmented graphics panel is updated with the corresponding content.

4.6 Interacting with volumetric multiplexed holograms

Volumetric multiplexed holograms[24] are digital multiple exposure transmission holograms that contain static CT, MRI or other volumetric datasets. They encode slices from a medical scan on a holographic film. The slices can be reconstructed simultaneously and appear as semi-transparent in space – resulting in a three-dimensional volumetric image. In contrast to many other 3D display techniques that are applied for viewing medical data, volumetric multiplexed holograms share the properties of other hologram types and support all depth queues. This is also the case for electroholographic displays. Some experiments have been made recently to use such devices for presenting time-series volumetric data[25].
Although the recorded content is static, volumetric multiplexed holograms can be augmented with interactive stereoscopic graphics.
The *Voxbox* display[24] is an analog light-box-like display that consists of a small tungsten halogen lamp, a front-surface mirror, and a sandwich of a Fresnel lens, a diffraction grating with dispersion compensation and a light directing film. It

is used to replay volumetric multiplexed holograms. The mirror of the *Voxbox* display virtually places the lamp at the focal point of the lens. The collimated light behind the lens is diffracted at an angle to reconstruct the hologram, and dispersed to cancel its strong dispersion effects. A louver film between the grating and the hologram blocks the zero-order light while letting the grating's dispersed spectrum pass through the hologram.

To integrate stereoscopic computer graphics into the hologram, we replace the halogen lamp and the mirror by two LCD projectors and mirror beam-combiners (cf. figure 12-top). The projected images are used to illuminate the hologram and to display colored stereo pairs at the same time. To ensure that a focused image is projected onto the holographic plane, the original Fresnel lens is replaced by a new lens with a focal distance of 1*m*. A 50/50 mirror beam combiner allows locating both projection centers at the lens' focal point. For separating the stereo images, we attach LC shutters in front of each projector's lens. These shutters are triggered in sync with the LC shutters of the observer's glasses by an external pulse generator at 100*Hz* or more. Air cooling prevents the LC shutters from being overheated. A normal (horizontal or vertical) alignment of the projectors would cause diffraction artifacts in form of visible Moiré patterns. This is because the raster of the projected pixels are in line with the orientation of the diffraction grating and the louvers of the light directing film. To minimize these artifacts, both projectors are tilted to a 45° angle around the projection axis. Note that in this case the LC shutters on the observer's glasses have to be rotated by the same angle to prevent light-loss caused by polarization effects. We use a wireless infrared tracking device to support head-tracking of the observer which is required for perspectively correct rendering of the graphics for different head positions.

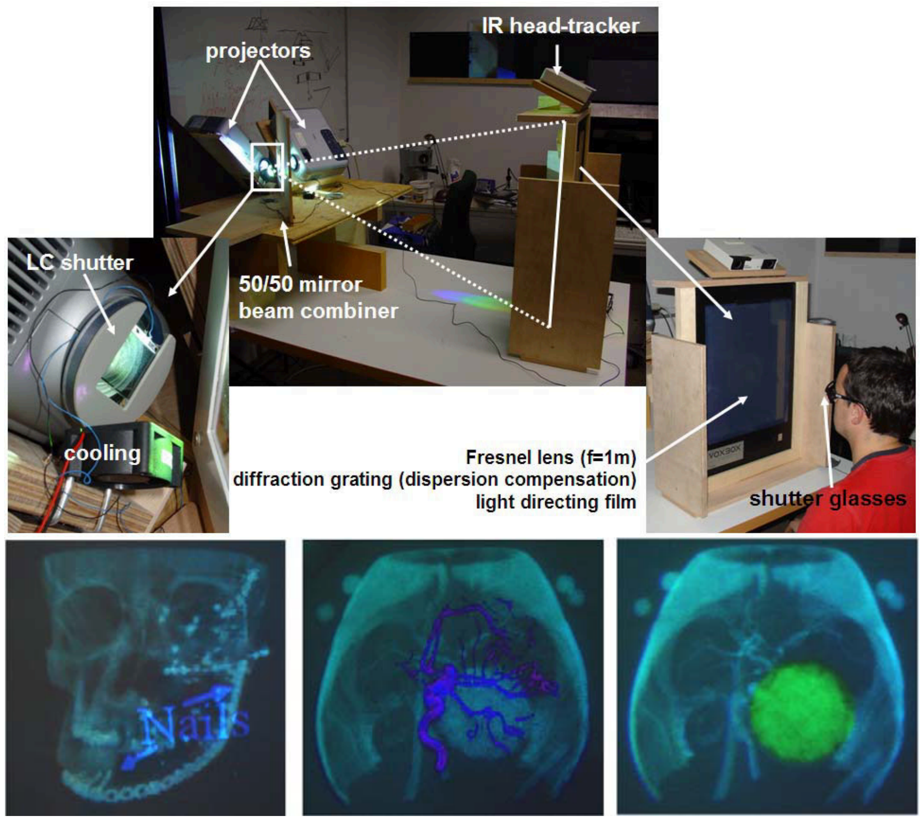

Figure 12: Prototype setup of modified *Voxbox* display (top), and sample results of holographic CT and MRI recordings with integrated stereoscopic graphics (bottom).

One projector displays the left stereo image while the other one displays the right stereo image. If the background of both images is white (or another gray scale), the holographic content is completely reconstructed. At those places where graphical elements are projected onto another color, the holographic content is blended with the graphical content. Thus, the graphical content appears also semi-transparent. A correct occlusion of holographic parts by graphical objects can only be achieved if the graphics is rendered in black (e.g., on a white background). This does not reconstruct the hologram in these areas. These techniques can be used to integrate interactive graphical augmentations into the hologram, or to color code different parts in a volumetric model, as illustrated in figure 12-bottom. This opens a variety of new interaction possibilities with volumetric multiplexed holograms, which still have to be explored.

5. CONCLUSION

We believe that electroholography will play a major role for future display technology. It has a high potential to provide a platform for a realistic and interactive visualization in many areas. However, several technological problems have yet to be solved before electroholography will be a useful alternative to three-dimensional computer graphics. Holograms support all depth queues. An important property which all other stereoscopic and autostereoscopic displays do not provide. However, non-electronic holograms are static and lack in interactivity.

We have described several rendering, illumination, interaction and reconstruction methods for combining optical or digital holograms with interactive computer graphics. While the holographic content can offer all advantages of holograms (i.e. extremely high visual quality and realism, support for all depth queues at no computational cost, space efficiency, etc.), the integrated graphical part is interactive. As illustrated, a variety of common hologram types, existing displaying methods, and application domains can be addressed with this concept. Computational intensive information, such as volumetric datasets or photorealistic scenes, for instance, can be represented with a hologram while interactive elements can be added with computer graphics. All of this is possible with off-the-shelf technology that is available today. This may lead to new tools for science, industry and education.

Our future work in this area focuses on the exploration of advanced rendering methods, suitable display configurations, useful interaction techniques and improved depth extraction algorithms. Receiving feedback from potential users will allow to refine and validate our concept.

ACKNOWLEDGEMENTS

We would like to acknowledge and thank Yves Gentet of the Yves GENTET - Art and Science holographic studio, Stephen Hart of Voxel Inc., Kaveh Bazargan of Focal Image Ltd, Tim Frieb of Holowood Holographiezentrum Bamberg e.K., Wilhelm Wilke of DaimlerChrysler AG, Holger Regenbrecht of Otago University, Steven Gatesy of Brown University, and Lawrence Witmer of Ohio University for their technical support and professional feedback. This project is supported by the Deutsche Forschungsgemeinschaft (DFG) under contract number BI 835/1-1.

REFERENCES

1. O. Bimber, *Combining Optical Holograms with Interactive Computer Graphics*, IEEE Computer, pp. 85-91, January 2004.
2. J.S. Kollin, S.A. Benton, and M.L. Jepsen, *Real-Time Display of 3-D Computed Holograms by Scanning the Image of an Acousto-Optic Modulator*, Proceedings of SPIE, vol. 1136, Holographic Optics II: Principles and Applications, Springer, pp. 178-185, 1989.
3. M. Lucente, *Interactive Three-Dimensional Holographic Displays: Seeing the Future in Depth*, ACM Computer Graphics, Special Issue on Current, New, and Emerging Display Systems, ACM Press, pp. 63-67, 1997.
4. M. Lucente and A. Tinsley, *Rendering Interactive Images*, Proceedings of ACM Siggraph’95, ACM Press, pp. 387-394, 1995.
5. M. Lucente, *Interactive Computation of Holograms Using a Look-Up Table*, Journal of Electronic Imaging, vol. 2, no. 1, pp. 28-34, 1993.
6. C. Petz and M. Magnor, *Fast Hologram Synthesis for 3D Geometry Models Using Graphics Hardware*, Proceedings of SPIE’03, Practical Holography XVII and Holographic Materials IX, vol. 5005, Springer, pp. 266-275, 2003.
7. F. Dreesen and G. von Bally, *Color Holography in a Single Layer for Documentation and Analysis of Cultural Heritage*, In Proceedings of Optics within Life Sciences (OWLS IV), Springer, pp. 79-82, 1997.
8. F. Dreesen, H. Deleré, and G. von Bally, *High-Resolution Color Holography for Archaeological and Medical Applications*, In Proceedings of Optics within Life Sciences (OWLS V), Springer, pp. 349-352, 2000.
9. T. H. Massie, and J. K. Salisbury, *The PHANTOM Haptic Interface: A Device for Probing Virtual Objects* Proceedings of the ASME Dynamic Systems and Control Division, vol. 55, no. 1, pp. 295-301, 1994.

10. M.R.E. Jones, *The Haptic Hologram*, Proceedings of SPIE, Fifth International Symposium on Display Holography, vol. 2333, pp. 444-447, 1994.
11. W. Plesniak and M. Klug, *Tangible Holography: Adding Synthetic Touch to 3D Display*, Proceedings of the IS&T/SPIE Symposium on Electric Imaging, Practical Holography XI, pp. 53-63, 1999.
12. W. Plesniak and R. Pappu, *Coincident Display Using Haptic and Holographic Video*, Proceedings of ACM SIGCHI conference on Human factors in computing systems, pp. 304-311, 1998.
13. W. Plesniak and R. Pappu, *Spatial Interaction with Haptic Holograms*, Proceedings of the IEEE International Conference on Multimedia Computing and Systems, vol. 1, pp. 413-426, 1999.
14. Y. Gentet and P. Gentet, *Ultimate emulsion and its applications: a laboratory-made silver halide emulsion of optimized quality for monochromatic pulsed and full-color holography*, Proceedings of SPIE'00, Holography 2000, vol. 4149, pp. 56-62, 2000.
15. D. Vila, *Folding Time into Space – Novel Approaches to Integral Holography,* Proceedings of SPIE'93, Practical Holography VII: Imaging and Materials, vol. 1914, Springer, pp. 230-235, 1993.
16. D. Vila, *Holo-Dynamics – Linking Holography to Interactive Media*, Proceedings of SPIE'93, Practical Holography VIII, vol. 2176, Springer, pp. 166-171, 1994.
17. M. Okamoto, H. Ueda, I. Nakamura, E. Shimizu, and T. Kubota, *Multiple Illuminations Method for Rainbow Holograms using an LCD Projector*, Proceedings of SPIE'97, Practical Holography XI, vol. 3011, Springer, pp. 70-75, 1997.
18. K. Yamasakia, M. Okamotoa, I. Nakamura, and E. Shimizu, *Fluctuation Hologram with Multiple Images*, Proceedings of SPIE'98, Practical Holography XII, vol. 3293, Springer, pp. 139-144, 1998.
19. J.R. Andrews and W.H. Haas, *Compact Illuminators for Transmission Holograms*, Proceedings of SPIE'89, Practical Holography III, vol. 1051, Springer, pp. 156-159, 1989.
20. J. Bongartz, D. Giel, P. Hering, *Fast 3D topometry in medicine using pulsed holography*, Proceedings of SPIE'02, Practical Holography XVI and Holographic Materials VIII, vol. 4659, 2002.
21. S. Frey, J. Bongartz, D. Giel, A. Thelen, and P. Hering, *Ultrafast holographic technique for 3D in situ documentation of cultural heritage*, Proceedings of SPIE'03, Optical Metrology for Arts and Multimedia, vol. 5146, pp. 194-201, 2003.
22. T. Carlsson, J. Gustafsson, and B. Nilsson, *Development of a 3D camera*, Proceedings of SPIE'99, Practical Holography XIII, vol. 3637, pp. 218-224, 1999.
23. N. Abramson, *Light-in-flight recording: high-speed holographic motion pictures of ultrafast phenomena*, Applied Optics, vol. 22, no. 2, pp. 215-231, 1983.
24. S.J. Hart and M.N. Dalton, *Display holography for medical tomography*, Proceedings of SPIE'90, Practical Holography IV, vol. 1212, pp. 116-135, 1990.
25. W. Plesniak, M. Halle, S.D. Pieper, W. Wells III, M. Jakab, D.S. Meier, S.A. Benton, C.R.G. Guttmann, and R. Kikinis, *Holographic Video Display of Time-Series Volumetric Medical Data*, Proceedings of IEEE Visualization, pp. 78-85, 2003.
26. E.B. Champagne, *Nonparaxial Imaging, Magnification, and Aberration Properties in Holography*, Journal of the Optical Society of America, vol. 57, no. 1, pp. 51-54, 1967.
27. K. Bazargan, *Techniques in Display Holography*, Ph.D. Dissertation, Physics Dept, Imperial College, London University, p. 16, 1986.
28. H. Liu and P. Bhattacharya, *Uncalibrated stereo matching using discrete wavelet transform*, Proceedings of 15th International Conference on Pattern Recognition, vol.1, pp.114-118, 2000.
29. C. W. Slinger, C. D. Cameron, S. J. Coomber, R. J. Miller, D. A. Payne, A. P. Smith, M. A. G. Smith, and M. Stanley, *Recent developments in computer generated holography: towards a practical electroholography system for interactive 3D visualization*, Proceedings of SPIE'04, Practical Holography XVIII, vol. 5290 ,pp. 27-41, 2004.