Holographic Images in Multimedia Information Systems

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Abstract

Multimedia information systems are based on the evolving capability of computers to handle diverse types of information. Their most important characteristic is the integration of all such information types.

Due to the improvements in computer architectures, computational methods, and electro-optical technology in recent years, a new type of information will soon be available, also outside research laboratories: electro-holography, that is the computer-based generation of diffraction fringes from 3D input data and the display of the reconstructed object in real-time.

This paper analyses which issues have to be solved in order to support the physical and logical coexistence and interactive use of holographic data in a multimedia information system. In particular the characteristics of holographic data and the current research results in the area of real-time holographic display systems are described. Besides, the requirements for integration of electro-holography into a multimedia system are analysed and the way this affects the functionalities of the system is described. The requirements on compression methods for holographic data are also discussed.

Keywords: electro-holography, computer-generated holography, multimedia information systems, encoding and compression methods.

Introduction

The area of multimedia is of great importance in information processing and is currently the central point of many research activities. The related technologies are changing so rapidly that it is important to look beyond the capabilities and requirements of the current technology and to support radically new developments, as already pointed out in [SC88].

The present 3D representation of images and graphics on a flat computer display in multimedia systems is becoming insufficient and an innovative way to handle light information is needed. This need could be satisfied by holography, and in particular electro-holography. In fact a holographic image can offer all depth-cues needed to

perceive image depth, such as perspective, binocular disparity, motion parallax, and in particular convergence and accommodation.
The integration of electro-holography into a multimedia information system, that is, embedding holographic images in other multimedia data types, presents new demands on the systems and on the related applications. The goal of this paper is to analyse which issues have to be solved in order to allow such integration.

Three different aspects should be considered:

- the formal aspect, in which a formal description of the information type is required;
- the technological aspect, oriented more to a functional analysis of multimedia systems, in relation to the integration of a new information type in system functionalities;
- the implementation aspect, in which some concrete information systems are defined.

This paper deals with the formal and technological aspects, analysing in particular:

- the characteristic specification of the new holographic information type;
- the definition of the data representation of this information type;
- the synchronisation with other information types;
- the interaction possibilities (in particular hyperlinks with other data types);
- the definition of the minimum set of hardware requirements.

Section 1 describes and characterises holographic images as new data type for multimedia systems. Typical applications of the integration of holographic images into multimedia systems are briefly illustrated. Section 2 reviews different technological approaches to produce synthetic holography, while section 3 is devoted to a discussion of the problems and issues specifically related to the integration of this new type of information into a multimedia system. Section 4 focuses on the issues of encoding and compression of holographic data and their conflicts with other requirements. The basic principles are explained and questions and items for future research shortly analysed.

1. Electro-Holography as New Media

In order to introduce the problems of integrating holographic images, this section reviews general information on the characteristics of such images.

Interference and diffraction of light are used in optical holography to record and reproduce 3D information of an optical wavefront. The synthesis of holograms by computers, based on the work of Kozma and Kelly [KO65], Brown and Lohmann [BR65], started in 1965. The recording process of optical holography with coherent light was simulated and Computer-Generated-Holograms (CGHs) produced as a numerical representation of an interference pattern with complex values. The enormous amount of samples needed to reach the resolution of optically-made holograms and the complexity of the physical model of light interference required computational resources not yet available in those years, preventing the development of a real-time holographic display. The first display system capable of displaying 3D holographic images in real-time appeared in 1989 with the Mark I Holographic Video System [KO89], at the MIT Media Laboratory Spatial Imaging Group.

Today the term “electro-holography” indicates the electronic form of holographic images, where such images are created dynamically. In electro-holography information is computed and encoded as discrete samples. These samples represent the fringe pattern of a computer-generated hologram. To reconstruct the 3D object, an electro-optical equipment (the holographic display) with a Spatial Light Modulator (in the following referred to as SLM) can be used to modulate the beam of light with the holographic fringe pattern.

Figure 1 shows schematically a generic real-time holographic display.

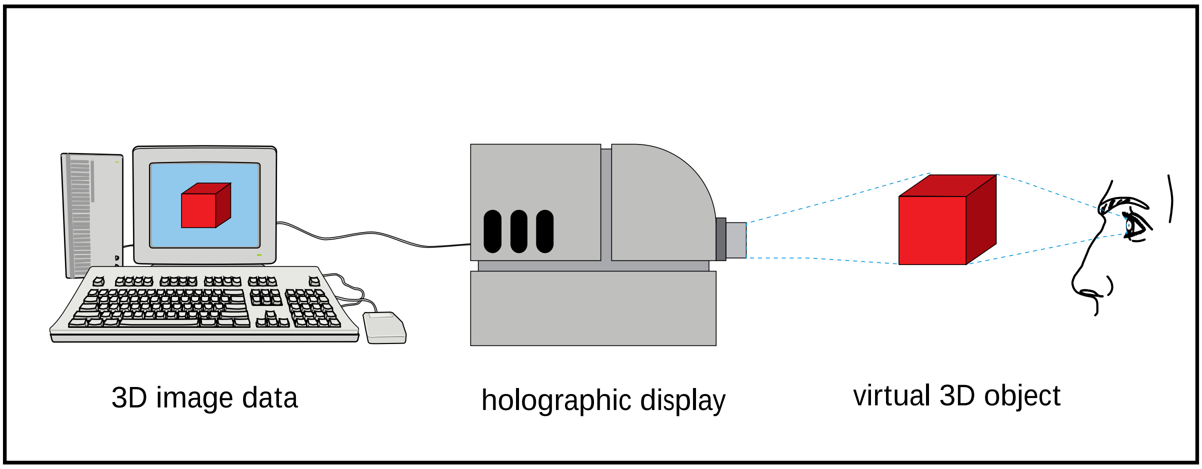

Fig. 1: A generic holographic display system

Processing Holographic Data

The following main difficulties arise in processing holographic data:

- the handling of an enormous amount of data;
- the computationally very expensive operations;
- the high resolution needed for the display unit;
- the high data rate needed for a real-time, interactive system.

It can be demonstrated that the management of the information content of full parallax holographic images is beyond the capability of the current technology. The number of samples for a full-parallax hologram is [ST94]:

$$N_T = 4\, d\, w\, \lambda^{-2} \sin^2 \theta_v \qquad (1)$$

where:
- λ = wavelength of the diffracted light
- θ_v = viewing angle (assuming that the angles subtended in the horizontal and vertical directions are the same)
- d = width of the hologram
- w = height of the hologram.

For example, to display a hologram with dimensions d = 100 mm, w = 100 mm, λ = 633 nm, and a viewing angle θ_v = 30°, a total number N_T = 25 x 10^9 samples is required. Real-time updating of such large amounts of data cannot be handled with the current computers´ speed. The solution has therefore to be searched starting from reduction and compression of the information to be handled.

Besides, the features of an interference fringe pattern have a size comparable to the wavelength of visible light (about 0.5 μm). The resolution of an hypothetical holographic display should match the dimensions of such features and should be capable of rendering spatial frequencies of 1500 linepairs/mm (lp/mm).

In order to reduce the information content of the holographic fringe patterns and to eliminate its information redundancy, different approaches were adopted. In fact most of the visual information of an hologram need not be used, because of the limits of the human visual system, that cannot make use of information with resolution in the micron range. A strategy for bandwidth compression should be capable of reaching information reduction without subsampling of the information content and maintaining a high image quality in the reconstruction process. Several methods for information reduction exist; the main ones are summarised in the following:

1) elimination of the vertical parallax; the so-called horizontal-parallax only (HPO) holograms are produced in this way ([DE68], [FR69], [BE82]). The reconstructed 3D image is limited to horizontal perspectives only and the display system must satisfy holographic resolution requirements only in the horizontal direction, not in the vertical one. In fact an HPO hologram can be considered as a set of 1D holographic lines, stacked together in the vertical direction. The features of every single holographic line diffract light only to a single horizontal plane of the reconstructed object. Due to the low vertical spatial frequencies (about 10 lp/mm), the elimination of the vertical parallax reduces the information content of a CGH by a factor of 100. This approach introduces an amount of astigmatism in the reconstruction process, which limits the usable range of depths in the reconstructed image. In fact the vertical information is centered at the image plane (in middle of the image volume), while the horizontal information focuses to a range of depths in the image volume. For example, the MIT holovideo system ([LU94]) has a range of depths of about 80 mm.
2) reduction of the horizontal viewing zone, that is, the range of the eye positions useful to see the reconstructed image. Together with the reduction of image size, this is the easiest method to reduce the bandwidth of the hologram (see equation (1)). On the other hand, the reconstructed image must be large enough to show binocular disparity, that is, both eyes of the viewer should see the diffracted light in the viewing zone. Otherwise the display system has to be considered as a 2D display. For a viewing distance of 600 mm and an intraocular distance of 65 mm, the minimum viewing angle results of 6.2°. In order to provide horizontal parallax, the viewing angle would have at least to be doubled, resulting in a minimum of 12.4° ([ST94]).
3) reduction of the image size. The same considerations, as for the previous point, are valid.
4) reduction of information content, based on the analysis of the human visual system parameters, such lateral and depth spatial acuities, and parallax resolution ([LU94]).
   In fact much of the hologram bandwidth cannot be used by the human visual system, which cannot resolve the smallest features that holography is capable of producing. For example, HPO holograms do not need to show continuously varying parallax also in the horizontal direction; the different views of the object that the observer sees will not be a continuous function of the viewing angle but will be a

discrete number of views, depending on the parallax resolution of the observer. Encoding and compression methods, capable of taking advantage of such results, are required. In this way a reduction of the horizontal display resolution is achieved.
5) non-uniform sampling of the hologram ([PA93]), in order to avoid the oversampling of some areas of the hologram, having smaller maximum spatial frequency.
6) encoding techniques, specific for holographic data (see section 4., [LU94]).

To achieve real-time and interactive display of the holographic images, the following methods can be adopted:

1) time-multiplexing of the holographic image ([AR92], [ST94]), in which different holographic lines are separately calculated and time-multiplexed by a series of lenses and scanning mirrors.
2) parallelism in the display system architecture ([ST94], [IW95]), using small display units, in order to form a large electro-holographic display.
3) new computing approaches, such as the "diffraction-specific computation“ ([LU94]). Traditional computing methods are based on the model of the interference of coherent light, occurring during the optical production of holograms. On the contrary, this method is based on a model of light diffraction, occurring when the image is reconstructed. Basic diffracting structures, the so called "basis fringes“, are precalculated and accessed using a look up table, to give their diffractive contribution for a single image element in the image volume.

It should be pointed out that holographic fringe patterns cannot be treated just as an image, because of their intrinsic information bearing capability. A complete analysis to determine the real information content of a hologram has not been achieved yet, although current studies on the holographic information transfer to a beam of light through a spatial light modulator ([PA95]) presented interesting ideas.

Holographic Data as Content Information Type

It is conceivable that future multimedia applications might require the integration of holographic information with other more classical information types.
Simple scenarios could be, for example, a compound document including a sequence of holographic data with hyperlinks to text or to 2D-3D graphics data, seen as explanations or further information to the holographic scene. Of course hyperlinks could also point to other holographic data.
Another example could be a computer-driven presentation in which a sequence of holographic data is accompanied by a soundtrack.

A central question to connect holographic data to information processing systems is to find for them a place in the architecture model of the system related to the information types. Using the classification of Brenner et al. [BR94], multimedia information can be grouped in the following types: access, structure and content information. Holographic data, produced and displayed in real-time with some of the techniques described in the next section or calculated and stored as encoded fringe patterns, can be considered as a new type of content information. Like audio and video, they can be considered continuous media and a data model as a formal basis for the management of holographic data could be an extension of existing data models for the other continuous media ([GA94]).

From this point of view, another important aspect that has to be investigated is the relationship between this new content type and the content type "image“. A basic model for the area of image communication and interchange, the so-called Image Communication Open Architecture ([ST93b]) has been elaborated. This model considers the different image representations and the relation between images and other media, especially audio. An interesting issue is to understand in which way the concepts of this model could be extended to include also holographic data.
In particular interchange formats have to be defined. Due to the demanding real-time requirements, this format should include a set of set-up information about the holographic display system and synchronisation information to map holographic data to other media types.

2. Different Technological Approaches to Holographic Display Systems

Different attempts have been made to display computer-generated holograms in real-time with an SLM. In this section, a general holographic display system and the two most promising implementation approaches are briefly described.
An electro-holography display system is schematically constituted by the following components (see Fig. 2):

- a 3D image processing unit, in which the 3D numerical description of an object is produced.
- a holographic data processing unit, in which the 3D description with different computational methods is transformed into the fringe patterns of the hologram.
- a signal processing unit, in which the fringe pattern is converted into a signal for the SLM.
- the display unit, composed by the SLM, lenses and eventually the mechanical scanning system.

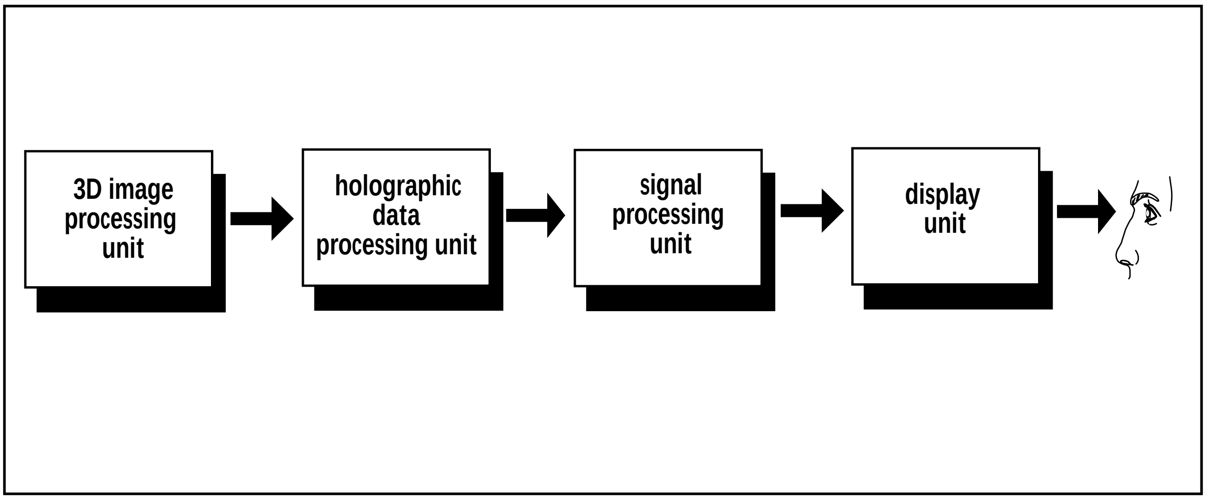

Fig. 2: Components of a holographic display system

Liquid Crystal Devices (LCDs) and Acousto-Optical Modulators (AOMs) are currently used as SLMs.
In holographic displays based on AOMs, the fringe pattern is transformed into a radio-frequency signal and passed to the AOM, that modulates a beam of laser light.

A system of lenses and scanning mirrors focuses the real 3D image in front of the output lens of the system. The Spatial Imaging Group at the MIT Media Laboratory was the first group to propose such a display system. To overcome the limitation imposed by the bandwidth of the AOM, a time-multiplexed AOM was used, in which 18 separated laser beams were modulated simultaneously ([ST93]).
A different approach was taken by Iwata and his group ([IW95]). Their work is based on a parallel architecture of multiple small units, consisting of a holographic data processing unit, a signal processing unit, and a display unit. In this system the 3D data of the original object are divided into different areas and their transformation and displaying are carried out in parallel.

Other research groups use an active matrix LCD display to modulate a laser beam. Due to the limited resolution of the LCD, the size of the reconstructed image is small and a narrow viewing zone is achieved. Some researchers have implemented various solutions to overcome this problem; for example a high-resolution one dimensional LCD was used ([TA95]); alternatively, an optical geometry with two lenses to demagnify a computer-generated Fresnel hologram can be selected. An advantage of this approach is the absence of a mechanical scanning system, as used when the holographic display is based on AOMs. The rapid improvement of the manufacturing techniques for LCDs bear the promise of a higher resolution and a better space-bandwidth product in the near future.

3. Integration of Electro-Holography into Multimedia Information Systems

An information system can be characterised by the following functionalities:

- the acquisition of the information
- the processing of that information
- the presentation of the information and links to other information data types
- the interaction of the user with the information
- the storage/retrieval of the information.
- the transfer/communication of the information

The integration of electro-holography into a multimedia system imposes demanding technical requirements on a system and affects all its functionalities.
In particular:

- *acquisition*: this first step concerns the acquisition of the 3D input data that have to be processed to produce the holographic images. This requires standard formats that allow the acquisition of data from remotely located rendering applications.

- *processing*: extremely powerful and specialised processing hardware is needed in order to avoid bottlenecks (bandwidth limitations). Spatial light modulators are required with a broad spatial frequency and a sufficiently large number of display elements, electrically addressable and rewritable in real-time.

  The minimum bandwidth B of a SLM is a function of the viewing angle θ_v and of the width of the hologram. For a HPO hologram the bandwidth B is:

  $$B = 2\, d\, n\, S \sin\theta_v\, \lambda^{-1}$$

where S is the refresh rate of the SLM, and n the number of scan lines.

For example, for S = 30 Hz, n = 100, λ = 633 nm, d= 100 mm and θ_v = 30°, the ideal SLM should have a bandwidth of quite 0.5 GHz, even for a HPO hologram where the information content is significantly reduced. This is beyond the limits of the current SML technologies.
The bandwidth of the frame buffer also has to be large enough to transfer the data from the holographic data processing unit to the SLM without bottlenecks.

With respect to this hardware specialisation it turns out to be particularly important to retain the localisation of device dependencies within isolated components of the multimedia system.

- *presentation*: holographic data can be processed by a system as a stand-alone data type or attached as an independent stream to a multimedia document. In the first case no links to other media or even synchronisation is required, and the integration into the information system is limited to the hardware requirements, specific for such data type.
The second case is the most interesting. The first problem to be solved in this case involves extending the concept of "link“ in such a way that it also works for relationships among holographic data and other media. The user should be able, for example, to touch a virtual object with a three dimensional pointing device and to get the eventually related information, or even other related holographic images. This requires algorithms capable of reconstructing the relationship between a particular area of the holographic image volume and the 3D input data. Image processing techniques could be applied then to identify a 3D image from a limited range within such an image. Computational algorithms for partial updating of holographic objects have already been implemented ([TA95]) and could be the basis for the development of "holographic links“. A commonly used approach to hypermedia systems, requiring the ability to maintain hyperlink information separately from data, could also be adopted for holographic data. It should be investigated wether the currently used standards for hyperstructures, like HyTime or MHEG also suit holographic information systems.
Another important issue related to the presentation of holographic data is their synchronisation with other media. This synchronisation can be required by the retrieval of compound documents, containing also holographic data, or by input events caused by the user. For example: a user presses a button of the holographic image of a radio with a 3D input device, and a music plays. Also by the acquisition of information, temporal relational constraints could be present, for example, by the acquisition of 3D input data related to audio.
Depending on the wished resolution of the synchronisation and on the kind of holographic data, two kinds of synchronisation techniques are possible [GI94]:

  - a start/stop synchronisation method
  - a frame synchronisation method

In the first case the temporal constraints are used to start or to stop the holographic data and other media, where a maximum tolerance is defined. The second method is more interesting for time-variant holographic data, that is, representing a scene changing with time. In this case the concept of "frame“ and a strategy to identify the frames have to be defined. When the holographic scene is composed by a sequence of holographic stereograms, a simple possibility could be to consider each holographic stereogram as a single frame.

A central role in the full integration of holographic functionality into multimedia systems is played by the quality range that can be offered. For this reason another interesting issue is the determination of holographic image quality. The development of techniques for quantitative image quality assessment will be based on the human visual system characteristics; besides, it requires the determination of system parameters in the CGH production and analysis of their control effect on the image quality. This issue is particularly important also in relation to encoding and compression methods.

- *interaction*: the consistency of the user interface for different media types is a very important issue. To handle holographic data an user interface should support 3D input through special devices and facilitate the operations strictly related to the production of holographic images also for untrained users.

- *storage/retrieval*: once the holographic fringe patterns are computed, they could be stored to be accessed another time or from another remotely located information system. Considering the size of the fringes, the major challenges for a storage system is to guarantee a presentation in real-time of the retrieved holographic data. Again problems of hardware limitations become very important. Holographic data are stored in a compressed form, based on specific data compression techniques (see Section 4), in which the decoding of data has to be simple and quick. Different access methods exist, but perhaps the most practicable is still the retrieval by an identifier, in which every holographic data object carries a tag. The second issue related to the retrieval of holographic data, as part of compound documents, is their synchronisation with other objects of different media types.

- *transfer of information*: depending on the class of the multimedia application, it should be possible to access holographic data remotely (in presentational applications) or in real-time (conversational applications). Due to the enormous amount of data to be transferred, the real-time performance is an important issue.

4. Holographic Data Encoding and Compression

This section deals with some aspects of the encoding theory that are important in the context of the integration of holographic images into multimedia systems.

In order to minimise the mismatch between the encoded model of the world and the information that has to be compressed, the optimum ratio between the information carried and coded by the hologram and the information that can be perceived by the human observer has to be found. The redundant information can be quantified in different ways and eliminated during one of the various steps in the hologram production pipeline. For this reason an interesting approach to describe holographic data encoding is to consider the holographic display system as a communication system (see also [LU94], [PA95]), schematically mapping the different units of a holographic system into the components of a communication system, as shown in figure 3. The information source of such a communication system is the 3D image data; different computational methods encode these data in the holographic data processing unit.

Encoded data are then transmitted, through the channel of the signal processing unit, to the decoder, that is the display unit. The decoder transforms the data into diffracted light that propagates to the viewing zone for the viewer. Normally the computation time of the encoding step and of the decoding step are trade-off quantities.

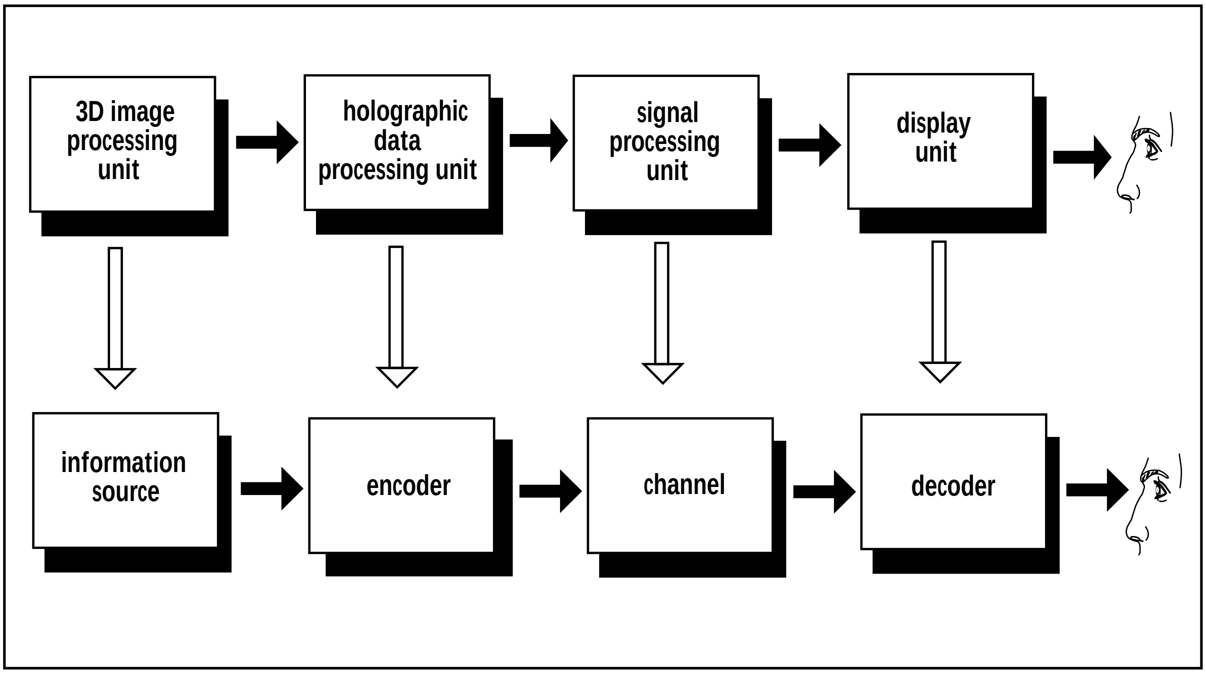

Fig. 3: A holographic display system mapped to a communication system

For electro-holography the primary goal of such a scheme is the reduction of the required bandwidth of the channel. For this reason different methods are used, as explained in section 1, and they can be considered the equivalent of lossy image compression methods for holographic data.

Two methods in particular are very interesting, the Hogel-Vector encoding method and the Fringelet method, both developed by Lucente ([LU94]). Based on the diffraction-specific computation, they allow a bandwidth compression ratio of 16 times, without a significant image quality degradation. Other results related to these compression methods are the reduction of the total time to compute the fringe patterns and a relationship between bandwidth, image resolution and image depth, as trade-off quantities.

Standard image compression techniques can also be used on already encoded fringe patterns, providing additional bandwidth reduction. It has to be investigated which lossless compression techniques are the most efficient for encoded holographic data.

The requirements on compression methods for holographic images which satisfy constraints with respect to access rates, network bandwidth and storage capability can be in conflict with other requirements about the flexibility of such methods to cope with the features of a multimedia system. In particular the following required characteristics of the compression method can constitute a problem:

- scalability: the encoded data could be used by different multimedia information systems. This could eventually require the modification of the decoding algorithm to adapt it to the different display geometry and resolution. The size of the viewing zone and of the image volume, and the sampling rate of the fringes are the parameters changing among different systems. Also compatibility with 2D display systems has to be supported.
- editability: ideally an encoding method should allow image processing manipulation and image updating without requiring decoding and re-coding of data.
- compatibility with other compression techniques for interoperability and the establishment of future standards.

Although some promising compression techniques have been developed, various open issues within the area of holographic data encoding remain. Some items for future research are:

- investigation on the non-linear characteristics of the human eye and their effect on the encoding techniques.
- definition of clear interfaces to compression software or hardware, in order to allow the use of different computational techniques.
- correlation among quality requirements and parameters of compression techniques.
- extension of the encoding methods to compute full-parallax holograms.

5. Conclusion and Future Work

Even if future research work is still needed to produce marketable holographic displays with a satisfactory quality of the holographic images and real-time interactivity, the growing demands for real 3D images coming from different application areas suggest that in the near future computer-generated holographic data will become commonplace. A shift in research focus will most probably occur from the development of holographic display systems as stand-alone applications to the co-ordination of such systems with the existing multimedia information systems.

The challenges related to the integration of holographic data as new content information into multimedia information systems are manifold and various. Technically the limits imposed by the hardware specialisation of a holographic display system have to be faced and encoding techniques capable of reducing the bandwidth requirements are the key point in this process. From the formal point of view some characteristic multimedia concepts, such as hyperlinks and synchronisation, have to be extended to match the needs of holographic data. A formal model for holographic data, including the definition of interchange formats, could be an extension of the current models for the data type "image“.

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