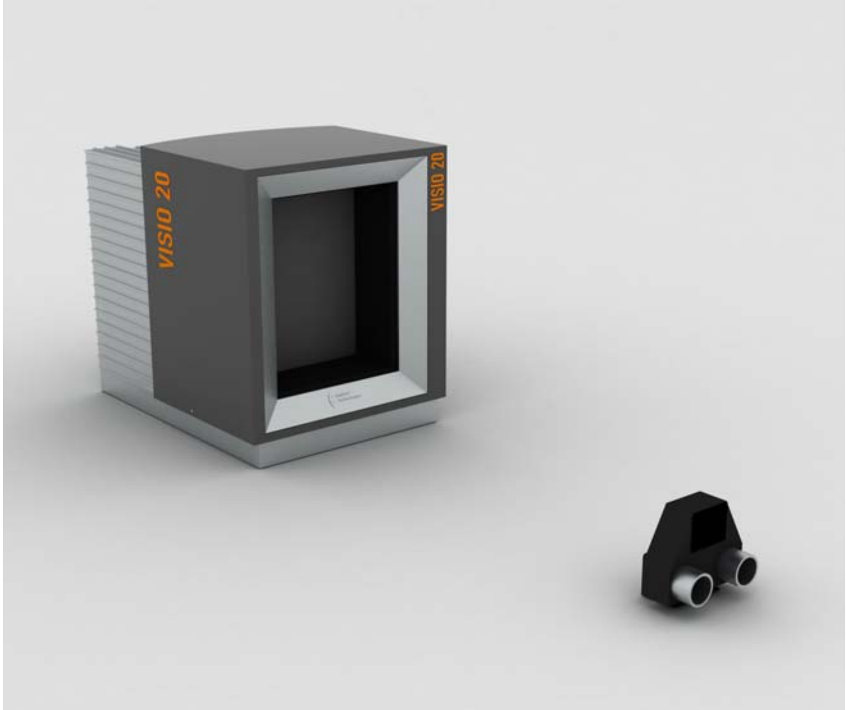
Large Holographic Displays for Real-Time Applications

A. Schwerdtner, R. Häussler, N. Leister
SeeReal Technologies GmbH, Blasewitzer Str. 43, 01307 Dresden, Germany

ABSTRACT

Holography is generally accepted as the ultimate approach to display three-dimensional scenes or objects. Principally, the reconstruction of an object from a perfect hologram would appear indistinguishable from viewing the corresponding real-world object. Up to now two main obstacles have prevented large-screen Computer-Generated Holograms (CGH) from achieving a satisfactory laboratory prototype not to mention a marketable one. The reason is a small cell pitch CGH resulting in a huge number of hologram cells and a very high computational load for encoding the CGH. These seemingly inevitable technological hurdles for a long time have not been cleared limiting the use of holography to special applications, such as optical filtering, interference, beam forming, digital holography for capturing the 3-D shape of objects, and others. SeeReal Technologies has developed a new approach for real-time capable CGH using the so-called Tracked Viewing Windows technology to overcome these problems. The paper will show that today's state of the art reconfigurable Spatial Light Modulators (SLM), especially today's feasible LCD panels are suited for reconstructing large 3-D scenes which can be observed from large viewing angles. For this to achieve the original holographic concept of containing information from the entire scene in each part of the CGH has been abandoned. This substantially reduces the hologram resolution and thus the computational load by several orders of magnitude making thus real-time computation possible. A monochrome real-time prototype measuring 20 inches has been built and demonstrated at last year's SID conference and exhibition 2007 and at several other events.

Keywords: CGH, video holography, real-time



1. INTRODUCTION

The worldwide increasing numbers of activities in 3-D stereoscopic display development in recent years have been focused on getting 3-D devices to the market. While in earlier years the development of stereoscopic displays have been emphasized for providing better features to compete with those of their 2-D counterparts now the entire chain from content creation to format standardisation to marketable 3-D displays and to broadcasting is dominating. This is evident when looking at the worldwide largest EU programme 3DTV[1], another EU program MUTED[2], the Korean Programs[3], and various programmes from research facilities and companies[4] .

Although stereoscopic 3-D display development focuses on market entry there remain still some issues which are in the way to a widespread consumer acceptance. These issues are known as human factors which arise from the depth cue mismatch between convergence and focussing of the observer's eyes viewing a 3-D scene. There are a considerable percentage of people who suffer from headache and other discomfort when viewing a stereoscopically produced 3-D scene. And these problems increase with viewing time.

In our opinion, this human factor problem principally inherent in all stereoscopy based displays has prevented so far the mass market entry.

Holography, recognized as the ultimate 3-D viewing technology, exhibits no such inherent obstacles but instead suffers from rather serious technological challenges.

The first and most serious challenge is connected to its underlying principle, namely diffraction. The CGHs is made up of diffracting elements called cells or pixels. The dimensions of the cells must be sufficiently small as to diffract the light over an angle from which the reconstructed object shall be observed. For a 60° diffraction angle the dimensions of the cell must be smaller than the wavelength of the light used for reconstruction. Making such reconfigurable CGHs does not appear feasible in the foreseeable future.

For example, a 20 in. wide CGH would need about 10^{13} hologram cells controllable in amplitude and phase. Today's state of the art TFT panels, often used as holographic CGH achieve a total number of about 10^{7} cells. The pixel dimensions of today's feasible direct view TFTs are in the range of 30 µm and larger instead of being smaller than 1 µm. So, several attempts have been made to tackle the problem for encoding reconfigurable holograms including a high resolution one-dimensional approach followed by vertical tiling the reconstructed lines to form a two-dimensional display[5]. Another tiling approach has been tried using a two-step process. In a first step parts of the diffraction pattern are imaged via fast ferroelectric LCDs onto a slower Optically Addressed SLM to assemble the entire hologram. After completing assembling the hologram is reconstructed to yield the final image[6] .

Encoding these holograms requires a giant computational load amounting to several tens or hundreds of PFLOPS (P: Peta).

Thus, if we really want to put a holographic video display on the market we need to strongly decrease the hologram cell resolution requirements. The novel approach for achieving this is described in the following section.

In the next sections we will focus mainly on the principle for achieving large screen holographic reconstructions that can be viewed from large observer angles as well as on real-time computation.

2. TRACKED VIEWING WINDOW APPROACH

The new approach is best understood when starting from a conventional hologram. A top-view schematic of a typical optical set-up for hologram reconstruction is shown in Fig.1. The 3-D scene is made up of multiple points with one point depicted in Fig.1. This point is encoded across the entire hologram. The same applies to all of other points of the 3-D scene. Hence, a conventionally encoded CGH requires a cell pitch as small as to enable the large diffraction angle α. This extremely high resolution of less than a wavelength of the light used requires a giant number of hologram cells even for a medium sized CGH. The small pitch is not only needed to diffract light into the diffraction angle α but it also avoids overlapping from higher orders into the diffraction order used.

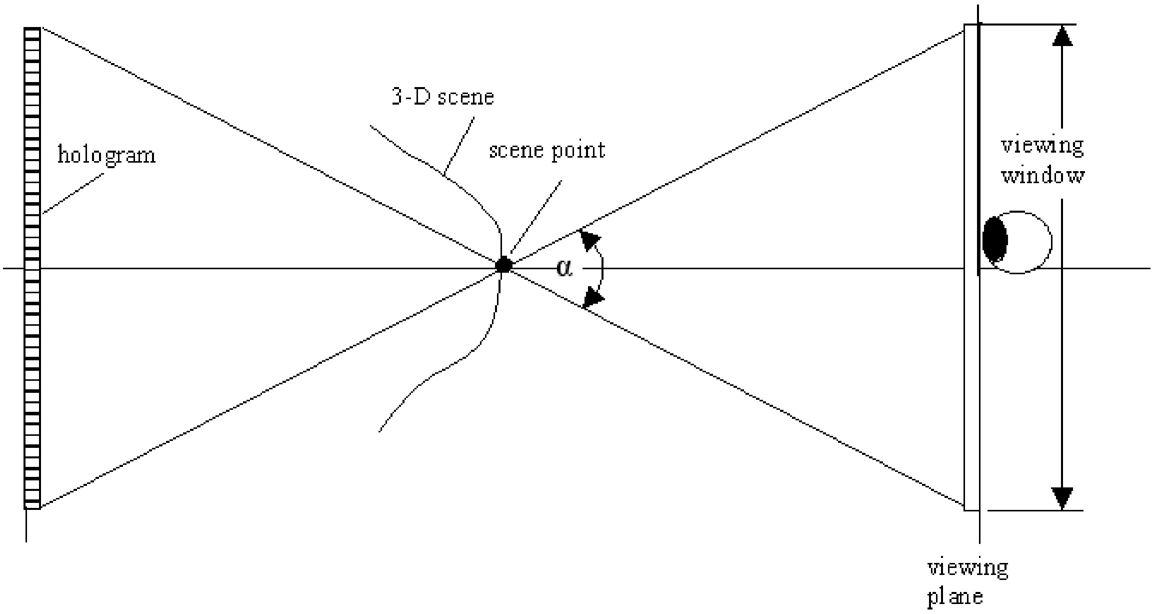


Fig. 1. Optical set-up for 3-D scene reconstruction from a conventional hologram. Each point of the 3-D scene is encoded on the entire hologram to form a viewing angle of say α = 60°.

From Fig. 1 it is quite obvious that the space at the viewing plane outside the observer's eye is not used. Thus, the viewing window shown in Fig.1 can be limited down to a size so as the observer with her/his eye can still comfortably see this reconstructed point and beyond this one all points of the entire 3-D scene. Encoded regions outside the down sized virtual VW may be considered a waste of information. After limiting the VW size that way (Fig. 2) no degradation of the reconstructed 3-D scene will be perceived by the observer. The observer looks through this VW into the direction of the hologram to view the 3-D scene. The virtual VW and the hologram span a frustrum. Within this frustrum and beyond the hologram a large 3-D scene can be reconstructed.

Because of the regular cell structure of the CGH we have to bear in mind that periodic replications of the reconstruction will occur. In order to make size and locations of the periodicity intervals independent of the hologram content and thus of the reconstructed 3-D scene we position the VW plane in the image plane of the illuminating light source. Mathematically, this plane is described as the Fourier plane of the hologram.

We require the virtual VW to be located completely inside one desired diffraction order, which is for reasons of high diffraction efficiency usually chosen to be the zero or plus/minus first diffraction order. We then confine the lateral size of the reconstruction in the virtual VW plane to lie completely within that one diffraction order. Thus, no overlap from higher orders will occur. With shrinking the lateral size of the Fourier transform of the hologram below or equal to one diffraction interval we have eliminated one of the most serious problems with CGHs. How to make the reconstruction fit within one virtual VW is explained with help of Fig. 2.

The fixed virtual VW located within the desired diffraction order is projected through each point of the 3-D scene onto the hologram. Each projected region defines a sub-hologram assigned in size and location to that point. Each sub-hologram on the hologram encodes one point only. Thus, each sub-hologram of specific size and location encodes a lens of appropriate focal length on the hologram plane. Regularly, many sub-holograms will overlap with each other. All complex-valued sub-hologram functions are then added up to form the final hologram function. This process of adding up does not effect or impair the reconstruction of the 3-D scene points as the law of superposition holds for electromagnetic fields here.

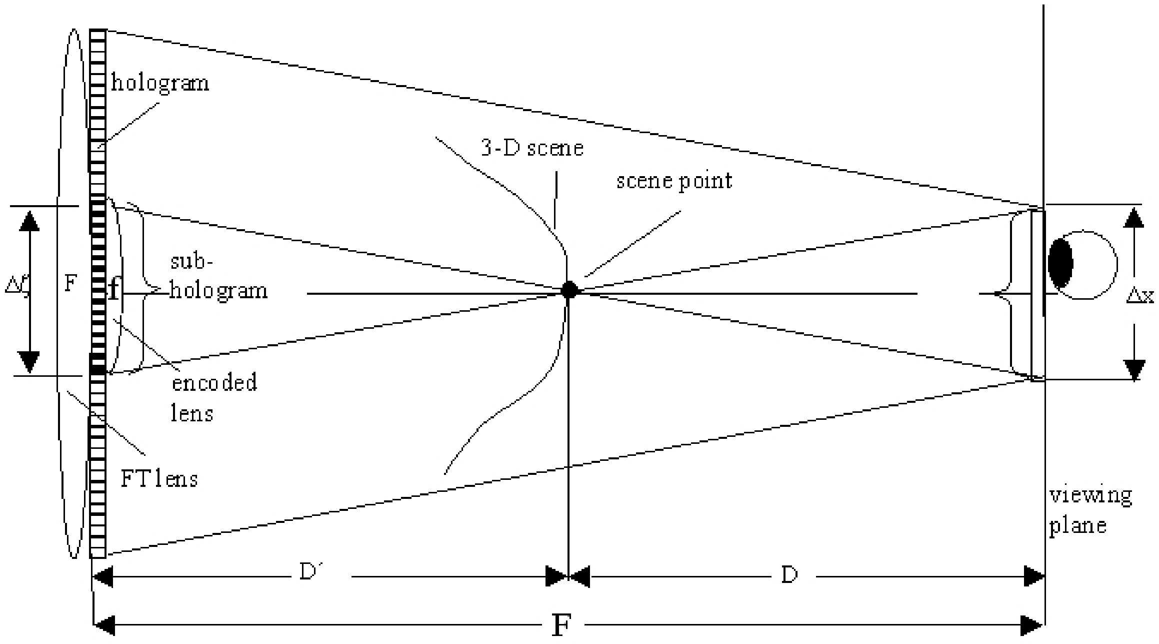


Fig. 2. Optical set-up with reduced VW size Δx. Only those parts Δζ of the hologram are encoded which are seen from the VW.

Using the sub-hologram construction described no adjacent or other diffraction orders will overlap into the virtual VW as they are constrained to regions outside the VW. This means, higher order reconstructions cannot be perceived as long as the observer's eye is located within the chosen VW.

Furthermore, as the diffraction angle realizing the small virtual VW is always almost very small hardly degradations due to the optical set-up will be observed. Moreover, each sub-hologram reconstructs its associated point on the optical axis of the encoded lens. Aberrations coming from the Fourier transform hologram can be easily compensated for in the encoding process.

The reconstruction for the other observer's eye may be generated in time sequential mode. The same applies to multiple observers. Time multiplexing can also be used for colour rendering.

For moving observers the virtual VWs need to be tracked to remain on the viewer's eyes. In a true parallax hologram the two-dimensional virtual VWs are tracked by changing the locations of the light source images. In our prototype we have implemented a one-dimensional encoding in the vertical direction. So, the vertical tracking is performed through vertical shifting the line light source images. For horizontal tracking direction we cannot generate a VW for tracking.

Instead, we use a beam splitter approach to assign the left and right eye image to the correct eyes. For horizontal tracking we re-encode the alternate columns for the left and right eyes

The normal distance of the observer from the holographic display must be kept to within several centimetres. Normal tracking is not provided in the prototype.

We call our novel technique Tracked VW (TVW) approach.

For comparison two display sizes for common 2-D usage, Tracked VW (TVW) CGH display and interference hologram are compiled. They are both assumed to provide monochromatic full HDTV resolution having an aspect ratio of 16:9 with the TVW-CGH VW size of 10 mm using a reconstruction wavelength of $\lambda = 500$ nm.

size		Viewer distance	Pixel/cell pitch	Total number of pixels/cells
20 in.	2-D Desktop monitor	-	359 µm	$2*10^6$
20 in.	TVW-CGH display	50 cm	25 µm	$2*10^8$
20 in.	Interfer. hologram.	-	0.6 µm	$3*10^{11}$
40 in.	TV	-	700 µm	$2*10^6$
40 in.	TVW-CGH display	2 m	50 µm	$2*10^8$
40 in.	Interfer. hologram.	-	0.6 µm	$1*10^{12}$

Table 1. Comparison of 20 in. desktop and 40 in. TV monitors and holographic displays. The comparison with the Tracked Viewing Window (TVW) holographic display shows a reduction in resolution by a factor of 10^3 - 10^4.

The Pixel number of the TVW holograms can be reduced by a factor of about 10^3 - 10^4.

The TVW approach differs in some respect from state of the art holograms.

Interference holograms are usually no Fourier transform holograms. The light waves interfere appropriately in space to form the 3-D scene. The observer can be located at any distance from the hologram. The price to be paid is the high hologram resolution needed.

In contrast, the TVW approach requires the viewer to be located at a distance close to the Fourier plane of the hologram and inside a virtual VW. This is accomplished by tracking normally to the hologram. As with lateral tracking normal tracking also requires repositioning the VW onto the observer's eyes.

We need to distinguish between two reconstructions of the hologram. First, the hologram is Fourier transformed into the light source image plane or VW plane and second, the reconstruction of the 3-D scene in the frustrum and beyond the hologram plane. The Fourier transformation of the hologram into the VW plane has already been described in detail. The reconstruction of the 3-D scene is done by the whole of the many sub-holograms. With respect to the Fourier transform just described this reconstruction is approximated rather by a Fresnel transform than a Fourier transform. But taking into account both lenses for any sub-hologram (Fig. 2), the Fourier transform lens and the encoded lens, the common focal point is the reconstructed point. The possible lateral size of the reconstructed 3-D scene is much larger than the periodicity interval that usually limits the lateral dimensions of a conventional encoded hologram. It increases to the hologram size approaching that plane and increases further for parts lying behind the hologram.

Employing the sub-hologram technology means we have relaxed a bit the definition of holography. Parts of TVW CGHs cannot reconstruct the entire scene as with conventional holography. If parts of the TVW hologram are not illuminated, for instance no longer the whole scene will be reconstructed. Instead, the effected sub-holograms will not contribute to the 3-D scene. On the other hand, the remaining hologram will reconstruct the hologram without any degradation in resolution, except for points at the margin illuminated. This also is different from conventional holograms.

3. COMPONENTS

Our goal we are pursuing targets developing true parallax video holograms.

But here, we will continue to describe the one-dimensional vertically encoded TVW hologram implemented as an intermediate step in our 20 inches wide prototype. A top-view sketch is shown in Fig. 3.

An array of LEDs is used to illuminate a shutter containing a variety of thin transparent horizontal lines (not shown) on a black screen (black/white LCD). For vertical tracking the lines can be shifted in the vertical direction. Light from these lines pass the horizontal lenticular placed after the shutter to become horizontally striped collimated light beams to illuminate the hologram. Each light line is assigned one lenticle with all lenticles imaging their line light sources into one line at the viewing plane. The lenticular acts as the Fourier transform lens. It replaces the large device depth caused by a big single lens with the small depth of a slim arrangement of lenticles. The shutter light lines are chosen thin enough to make the TVW hologram reconstruct small sized reconstructed points. The light lines emerging from the shutter are horizontally incoherent. Accordingly, the TVW hologram is vertically one-dimensionally encoded with the left-eye content and the right-eye content contained in alternating columns. The horizontal assignment of the left eye columns to the left eye and the right eye columns to the right eye is made by a lenticular beamsplitter in front of the SLM (Fig. 3).

While in the vertical direction the virtual viewing windows VW are formed having the size of one diffraction interval the horizontal assignment to the eyes is by viewing zones VZl, VZr for the left and right eye, accordingly formed by a beam splitter.

So far complex-valued cells have been used to describe encoding holograms, especially CGHs. But, up to now, CGHs with complex-valued cells have not yet been on the market.

Traditional hardcopy holograms use positive-valued light interference pattern imaged onto photographic plates or the like. Sometimes this approach is also used for CGH resulting in a considerable loss of resolution.

Very early so called detour-phase holograms have been developed. Each hologram cell contains an opening with an area or gray level determining the amplitude in the cell. The phase is given by the location of the opening within the cell (Lohmann et al.[7]) .

Burckhardt[8] decomposed the complex number into three components having a phase difference of 0°, ±120°. This made equidistantly spaced sub-cells possible which are more printer friendly.

As SLMs based on Liquid Crystal can easily made for encoding phases phase holograms became attractive. Among the phase holograms so called kinoforms[9] have gained particular attention. Here only the phase of a complex hologram value is used resulting unfortunately in noticeable reconstruction errors. A single lens can principally be kinoform encoded without any errors. However, our TVW approach requires summing up many sub-holograms containing encoded lenses. This leads to the known dynamic effects with holograms to produce one or several high magnitude peaks with the majority of cells containing low magnitude values. These effects translate directly to high amplitude bit depth of complex-capable holograms.

To alleviate the high dynamic range problems inherent in all CGHs the 3-D scene is point-wise modulated by a random phase.

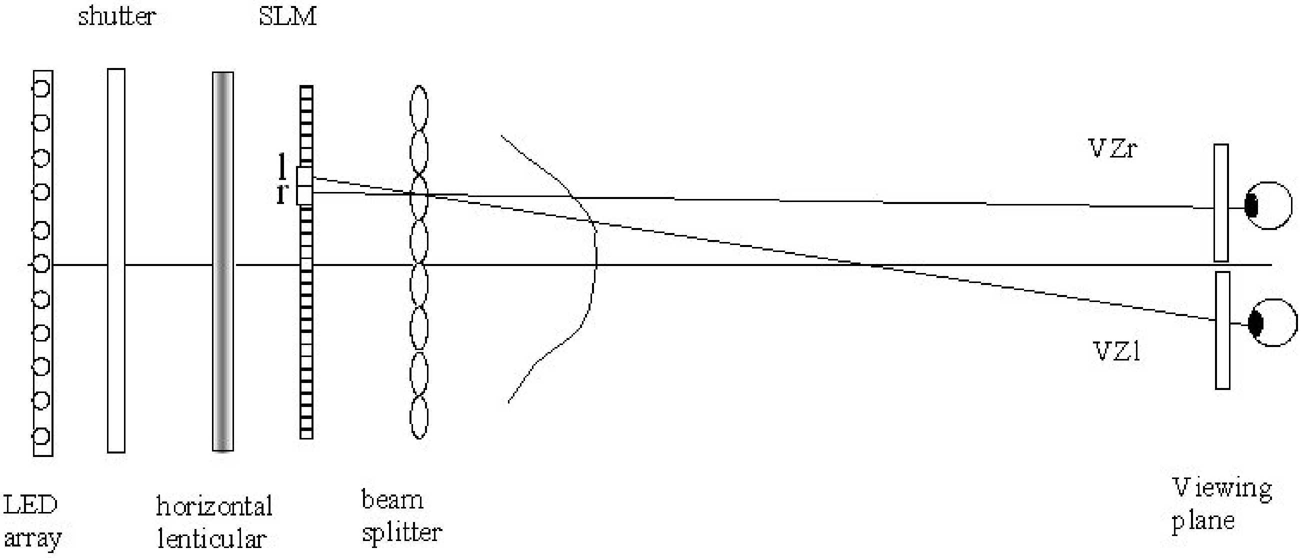


Fig. 3 Set-up for 1-D vertically encoded hologram. The horizontal lenticular converts the line light sources of the shutter to vertically coherent beams. Alternating columns are encoded with left eye and right eye images. Both images are projected onto proper eyes by beamsplitter.

4. TRACKING

Generally, moving observers are tracked by appropriately positioning the virtual VWs onto the viewers´ eyes. In our prototype this is done by vertical shifting the lines of the shutter. The content may or may not be changed. Horizontal tracking the viewing zones is employed by updating the holographically encoded columns with the appropriate information belonging to the new positions. As the light lines in our prototype are horizontally extended no light source tracking in this direction is needed.

The observers' eye's positions are detected using an eye finder camera located on top of the holographic display. The data of the camera are fed to an eye finder hardware unit which is based on FPGA hardware. The overall up-date time achieved from the observer movement up to repositioning the virtual VW and VZ is 60 ms. A position accuracy of 2 mm is achieved.

5. COMPUTATIONAL LOAD

As shown in table 1 the resolution requirements can be met using today's TFT technology. Other holography capable SLMs are likely to put on the agenda of SLM manufacturers once video holography is shown feasible for market entry.

Another issue is computation. A true-parallax TVW hologram with its strongly reduced number of cells compared to traditional CGH as well as the TVW sub-hologram technology greatly decreases the computational load. As each sub-hologram separately encodes a lens of given size, location, and focal length which are subsequently added up together to form the final hologram, extensive use of look-up tables (LUT) are attractive. Location and size determine the entry point into the LUT while the focal length defines the choice of the proper LUT.

Furthermore, as the sub-holograms are independent of one another the computation can be performed by extensively taking advantage of parallelization. The major LUT operations are by computing the entry points. A good hardware candidate for performing such a task is a FPGA or ASIC design.

For our one-dimensional TVW hologram prototype we can employ today's graphic cards. We use a GeForce8800 GTX board from NVIDIA to achieve a delay time of 30 ms from observer movement to positioning the VW and VZ (viewing window and viewing zone).

6. SUMMARY

SeeReal Technologies has developed a novel hologram technology called Tracked Viewing Window (TVW) approach enabling real-time large screen CGHs using today's state of the art SLMs, in particular TFTs. Instead of reconstructing a hologram into a wide viewing angle requiring an extremely fine structured CGH not feasible in the foreseeable future the reconstruction is confined to a small viewing window VW covering at least one eye of the observer. The other eye is served in a time sequential mode. The same applies to several observers and to RGB colours. Observer mobility is achieved through tracking the light source image onto the observers' eyes. This strongly reduces the resolution requirement as well as the computational load.

A real-time interactive 20 inches wide prototype employing 1-D encoding has been built and demonstrated at various events.

REFERENCES

[1] MULTIMEDIA, NEW TECHNOLOGY-3D TV could be a reality 'in a few years'. Citation from European Research Headlines from 23 Oct. 2006, "3D TV could be a reality 'in a few years'", http://ec.europa.eu/research/headlines/news/article_06_10_23_en.html

[2] Phil Surman, Ian Sexton, Klaus Hopf, Richard Bates, Wing Kai Lee, Edward Buckley, “Multi-User 3D Display Using a Head Tracker and RGB Laser Illumination Source”, XV International Symposium on Advanced Display Technologies, Proc. of SPIE Vol. 6637, 66370 (2007).

[3] Seung Cheol Kim, Purev Shukhbat, Eun-Soo Kim, “Three-Dimensional Reconstruction using Integral Imaging Technique of Captured Images by Holographic Method”, Optics and Photonics for Information Processing, Proc. of SPIE Vol. **6695**, 669514 (2007).

[4] Oscar H. Willemsen, Siebe T. de Zwart, Wilbert L. IJzerman, Martin G.H. Hiddink and Tim Dekker, „2D/3D switchable displays“, Photonics in Multimedia, Proceedings of SPIE Vol. **6196**, 61960H (2006) .

[5] D. E. Smalley, Q. Y. J. Smithwick, and V. M. Bove, Jr., “Holographic Video Display Based on Guided-Wave Acousto-Optic Devices,” *Proc. SPIE Practical Holography XXI*, **6488** (2007).

[6] Chris Slinger, Colin Cameron, and MauriceStanley, “Computer-Generated Holography as a Generic Display Technology“, Computer (IEEE Computer Society), 2005, August, pp 46 – 53.

[7] B. R. Brown, A. W. Lohmann, “Computer-generated Binary Holograms”, IBM J. RES. DEVELOP. , MARCH 1969, pp 160 – 168.

[8] C.B. Burckhardt, “A simplification of Lee´s method of generating holograms by computer”, Appl. Opt. 9, 1949-1949 (1970).

[9] L.B. Lesem, P.M. Hirsch, and J.A. Jordan Jr., ”Digital Holograms and Kinoforms”, Phase Shaping Objects, IBM Publication 320, 2248 (1968).