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Full-color interactive holographic projection system for large 3D scene reconstruction

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ABSTRACT

Dependence on sub-micron pixel pitch and super-computing have prohibited practical solutions for large size holographic displays until recently. SeeReal Technologies has developed a new approach to holographic displays significantly reducing these requirements. This concept is applicable to large “direct view” holographic displays as well as to projection designs.

Principles, advantages and selected solutions for holographic projection systems will be explained. Based on results from practical prototypes, advantageous new features, as large size full-color real-time holographic 3D scenes generated at high frame rates on micro displays with state of the art resolution will be presented.

Keywords: holography, 3D display, projection, LCoS,

1. INTRODUCTION

Although 3D displays in general are known for a long time they have become a field of increasing research activities in recent years. Major display manufacturing companies have developed prototypes or even products of 3D displays, for example Samsung¹. Such displays are of the stereoscopic type. They do provide the observer with different images for left and right eye as would be the case in a real word scene but in contrast to the real word experience both images are still flat. A well-known drawback resulting from this fact is the mismatch of eye convergence and accommodation, which may lead to eye strain and fatigue. This puts a limit to the depth range of the 3d scene shown on a stereoscopic display².

Whereas the rise of stereoscopic displays is an important step towards 3D – and our company SeeReal technologies itself has developed advanced designs of mature autostereoscopic systems³ - on the other hand it is widely accepted that the ultimate 3d display solution would be a holographic one.

Nevertheless the emergence of large scale holographic displays has long been hindered by severe obstacles. The most important problem for creation of a large size video hologram is related to the space-bandwidth product. In a sampled hologram the diffraction angle is proportional to the inverse of the pixel pitch of the hologram medium. Whereas large holograms on film materials with fine resolution are common, this is difficult to achieve for an electronic display. In classical holography a display with a pitch in the range of one micrometer is needed. The second problem connected to the first one is the tremendous computer hardware requirements for hologram calculation with a display having huge number of small pixels.

In some applications micro displays with a pixel pitch of a few micrometer are used for holographic reconstruction but in contrast to common projection applications these displays are not magnified. Instead they are used in a direct view mode limiting the size of the holographic reconstruction to very small dimensions. The combination of a large number of micro displays has also been proposed⁴ but leads to an extensive and costly setup.

Even very sophisticated approaches⁵⁻⁷ for holographic displays are limited to relatively small reconstruction volumes.

Our company SeeReal Technologies has developed a new approach to holographic displays. This was published and demonstrated for the first time May 2007 at the SID Conference and Exhibition⁸. This approach overcomes previous limitations. A holographic reconstruction of the wave field that would be generated by a real existing object is obtained at - but only at - the observers eye position, and nowhere else. This special configuration allows to use displays with relatively large pixel pitch. In our 20 inch prototype a state of the art high resolution desktop LCD panel was used with a pitch of about 70x210 μm .

In this work we show that it is also possible to make use of micro displays in such a setup but - in contrast to holographic reconstructions with micro displays described so far - we are able to magnify those micro displays to a screen. By making this we get a holographic projection system with hologram reconstruction in a large volume between screen and user.

This paper is structured as follows: in section 2 we shortly review the main features of the SeeReal approach, namely observer window and subhologram. For further details about these features we refer to⁹. In the third section the principle of the projection setup is discussed. Section 4 is related to holographic color reconstruction as the original SeeReal direct view prototype was monochrome and we did the first demonstration of the SeeReal approach with color reconstruction on the 8 inch projection prototype. In Section 5 components of the 8 inch prototype setup are discussed. Section 6 gives experimental results of hologram reconstructions with the prototype. Section 7 is related to user tracking.

2. SEEReAL'S REAL-TIME HOLOGRAPHIC DISPLAY SOLUTION

In classical holography - where the primary goal is to reconstruct the object itself - a large part of the information generated is not actually used. In contrast to this the primary goal of the SeeReal approach is to reconstruct only that part of the wavefront originating from the object, that actually hits the eye pupil of an observer. A wavefront in a small region, called observer window is reconstructed. The size of the observer window is related to the size of the eye pupil. The observer window may be located in the Fourier plane of the hologram. A separate observer window for each eye is generated either by spatial or by temporal multiplexing. Then the size of the observer window - and not the size of the reconstructed scene - determines the pixel pitch needed on the display.

Closely related to the concept of the observer window is the subhologram. For each reconstructed object point there is only a limited region in the hologram where data related to this object point is coded – in contrast for example a Fourier hologram, where each point in the Fourier plane can be related to the whole hologram area. This limited region is called subhologram. Figure 1 shows 2 object points located at different depth and their subholograms being of different size.

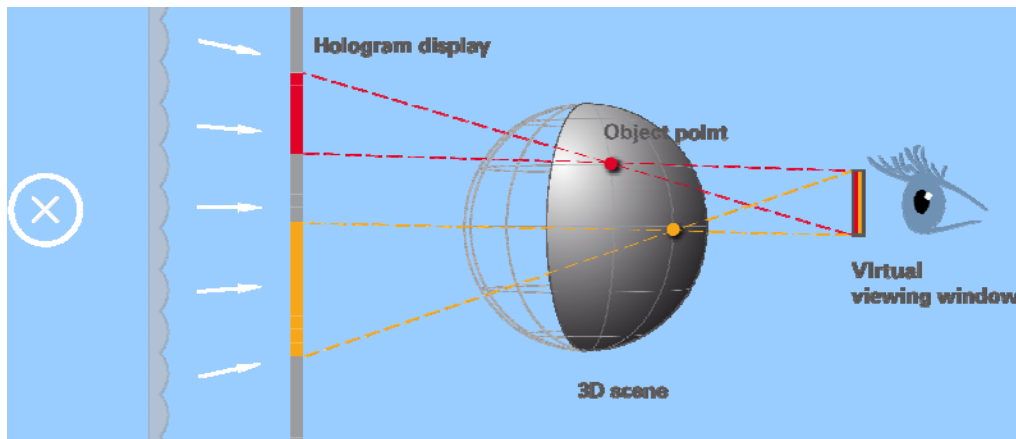


Fig. 1. Schematic: SeeReal direct view setup: From left to right Light source (actually a light source array is used), lens array, hologram display with position of 2 subholograms marked by colors, 3d scene, observer window and eye of the observer

The subhologram is coded as a phase function. The refractive analogue to a subhologram is a small lens. But in contrast to this analogue additionally the intensity of the reconstructed point can be controlled by setting the amplitude of the subhologram and also many subholograms of different object points may overlap. Holo calculation can be done by use of simple lens phase functions, multiplying them with an amplitude factor and then summing up individual subholos. No Fourier transform is recommended. This allows for real time calculation of the hologram.

Large reconstruction volume of the 3d scene is possible. The size of the reconstruction is only limited by the size of the hologram display used. The reconstruction is located in a frustum ranging from the observer window to the borders of the display and beyond. Movement of the observer is allowed by user tracking. The observer window can be shifted to the actual eye position for example by movement of the light source.

The direct view setup is illustrated schematically in figure 1. A light source is imaged by a lens to an observer plane. In principle a single light source and single lens may be used. In case of large displays it is more easy to take a light source

array in combination with a lens array instead. This is indicated by the lens array in the figure 1. The hologram display is located close to the lens array. A scene reconstruction is visible for an eye located inside the observer window. In the figure this reconstruction is shown between display and user, in general it can also be located fully or partly behind the display.

3. SEEReAL PROJECTION SETUP

The principle of the holographic projection setup is shown in figure 2. A light modulator, on which the hologram is coded, is located at position z_0 . This light modulator is illuminated with an expanded coherent light beam (indicated by a light source and a lens at the left in the figure). A magnified image of the light modulator is generated at the position of a screen z_3 by a lens located at z_1 . In between z_1 and z_3 there is a position z_2 where the Fourier transform of the SLM data is generated. In case of illumination of the SLM with parallel light this would be the focal plane of the lens at z_1 . In this plane filtering is done and by this way higher diffraction orders are eliminated. With a focusing element at the position z_3 i.e. at the screen the filter plane is imaged to the observer window.

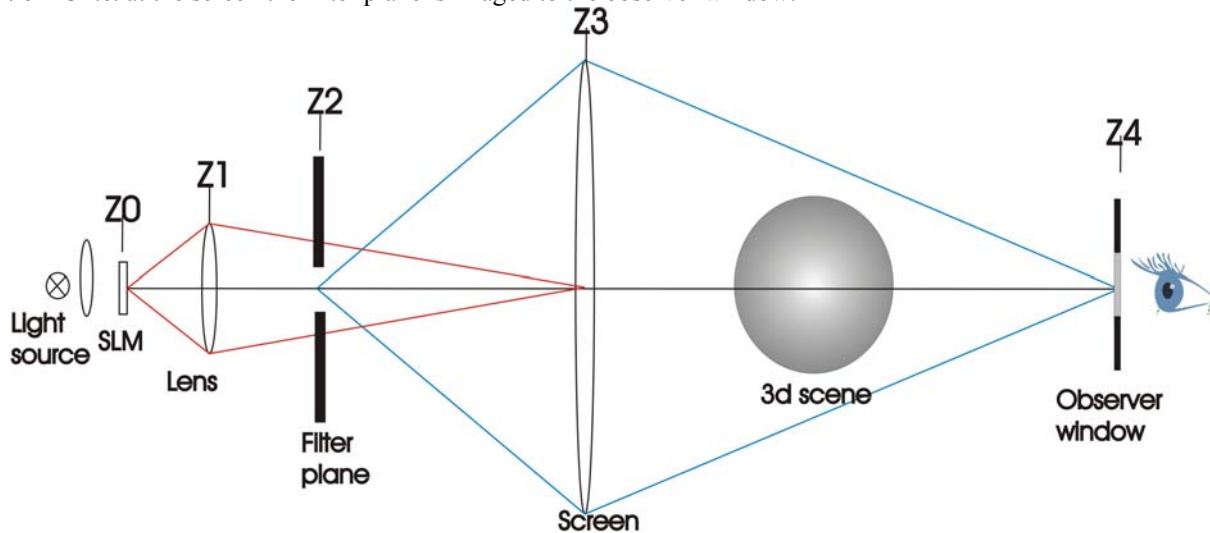


Fig. 2. Schematic: SeeReal projection setup

So this is a two way imaging system – a magnified image of the SLM itself is generated at the screen position, whereas the Fourier transform of the SLM data is imaged to the observer window. The screen replaces the hologram display in a direct view setup. An eye pupil located inside the observer window can see a 3d scene inside a frustum ranging from the eye to the border of the screen and beyond.

For sake of simplicity this scheme is shown with transmissive components where in a real setup reflective devices are used for SLM and for screen.

For a projection setup additional optical components are needed compared to a direct view setup. On the other hand there are several advantages. For example the illumination of the SLM can be done with a single light source for each color where in a direct view setup an array of light sources is recommended. So the use of compact laser light sources is possible in this case.

Use of micro displays gives more flexibility in terms of available display types and of display parameters. The observer window is not only related to the pixel pitch of the display but to the magnification of the projection optics as well. So there are more degrees of freedom in order to adapt the system to the intended observer window parameters. There is no need for a specially designed display with an optimized pixel pitch value.

Another feature not available in the direct view setup is the possibility of filtering higher orders with some kind of 4f setup. It has to be mentioned here that higher orders in case of an observer window type hologram are further less critical as they are in classical holography. Higher orders do not directly deteriorate the quality of the reconstruction - at least not for one single observers eye. Instead they lead to periodical repetitions of the observer window. So there exist higher order points for each scene point in the 3d scene but these are not visible from within the zero order observer window. But higher orders can be a possible reason for crosstalk between right eye and left eye observer window of one user – depending on the setup actually chosen - or may cause crosstalk between different users in a multiuser

holographic system. That is the case when either the other eye/a second user is bothered by higher orders of the first user/first eye observer window. Usually this crosstalk can be reduced to values below noticeable threshold in a direct view setup if additional features are implemented. Nevertheless use of a filtering unit in a projection setup is an easy way to get rid of higher orders.

In a direct view setup the size of the observer window is directly related to the pixel pitch p of the display, the reconstruction wavelength λ and the observer distance D by the equation $w = \lambda D / p$

In the path of rays in the projection setup a magnified SLM image is directly related to a smaller diffraction angle. The size of the observer window is given by $w = \lambda D / p_{im}$ where now p_{im} is the size of the magnified image of an SLM pixel. In terms of the subhologram as coded lens the projection setup can be interpreted in 2 ways.

One way is that the subhologram itself is imaged from the SLM to the screen acting as a coded lens on the screen, this coded lens generating the object point. The other way is: the subhologram can be seen a coded lens on the SLM generating an object point in a volume between SLM and filter plane and the whole object reconstruction is imaged from there to the frustum. In terms of hologram calculation both interpretations lead to the same result.

In any case: the subhologram consists of a lens function coded as quadratic phase term. Magnifying the area of the subhologram while maintaining the phase values leads to a lens function again but with different focal length of the lens. To sum up: for hologram calculation the same procedure can be applied as in a direct view setup, all distances referring to the screen and with the only difference of exchanging the pixel pitch itself in case of the direct view display with the magnified image of the pixel pitch on the screen in case of the projection setup.

4. OBSERVER WINDOW TYPE COLOR HOLOGRAM

The 8 inch projection prototype has been the first of SeeReal's prototypes where a full color reconstruction was demonstrated, whereas the original direct view prototype was monochromatic. Some aspects of color reconstruction will be discussed in the following.

Wavelength dependence in holography is related to different size of a diffraction order. As the diffraction angle is proportional to the wavelength λ it follows that in a conventional Fourier or Fresnel hologram a change in illumination wavelength leads to a different scale in the reconstructed object. In order to do a color reconstruction this has to be taken carefully into account in the hologram calculation. The position of single object points in the reconstruction is sensitive to small wavelength changes. This may easily deteriorate the quality of a conventional holographic color reconstruction in case of wavelength shift of the light sources.

With the SeeReal approach this is different: What changes with wavelength is not the reconstructed scene itself but the size of the observer window. This means for example that in an untracked system the eye pupil may move around somewhat further for a reconstruction with red light and still see the 3D scene than would be the case for a reconstruction with blue light. But the lateral position of the reconstructed points in space remains unchanged for red green and blue. There is only a small z-shift of the object points with wavelength. That also means that in principle LED light sources can be used for each color instead of a laser, as has been done in the SeeReal direct view prototype. The use of lasers in the projection prototype is due to easier optical setup of the illumination system in this case. In principle this system would also work with LED.

In the central area where all 3 RGB observer windows overlap there is a consistent color reconstruction. The requirement for good color reconstruction is fulfilled, in case the part of the observer window actually used is limited to the dimensions of the observer window of the smallest wavelength in the system – for an RGB systems this means blue. In the projection setup this is achieved by adapting the aperture of the filter unit to the size which corresponds to the blue wavelength observer window.

Whereas some upper limit of the observer window is given by the sampling theorem, it is easily possible to reduce the size of an observer window to smaller dimensions by coding some kind of black area in the Fourier plane. So by directly reducing the size of the red and green observer window to the blue one during the hologram calculation then light loss due to filtering may be minimized.

The hologram calculation is made from an input format 2d + depth map. This has the major advantage that existing 3d content can be easily converted to holographic output. So for calculation of a color hologram each 2d image is decomposed in its red, green and blue part, and then a red, green or blue hologram can be separately calculated using the depth map information common to all 3 holograms. The combination of reconstructions of these 3 holograms – which can be done by either spatial or temporal multiplexing, the latter actually used - leads to the observed 3D color scene.

5. COMPONENTS OF THE 8 INCH PROJECTION PROTOYPE

The components used in the 8 inch prototype are described. As a separate observer window for each eye is needed. In general this can be done either by spatial or temporal multiplexing. In the setup of the prototype a solution was chosen where two separate paths, one for each eye are built, so that apart from the screen itself, common to both eyes, all other components described in the following exist twice. In figure 3 only the components for one eye are shown.

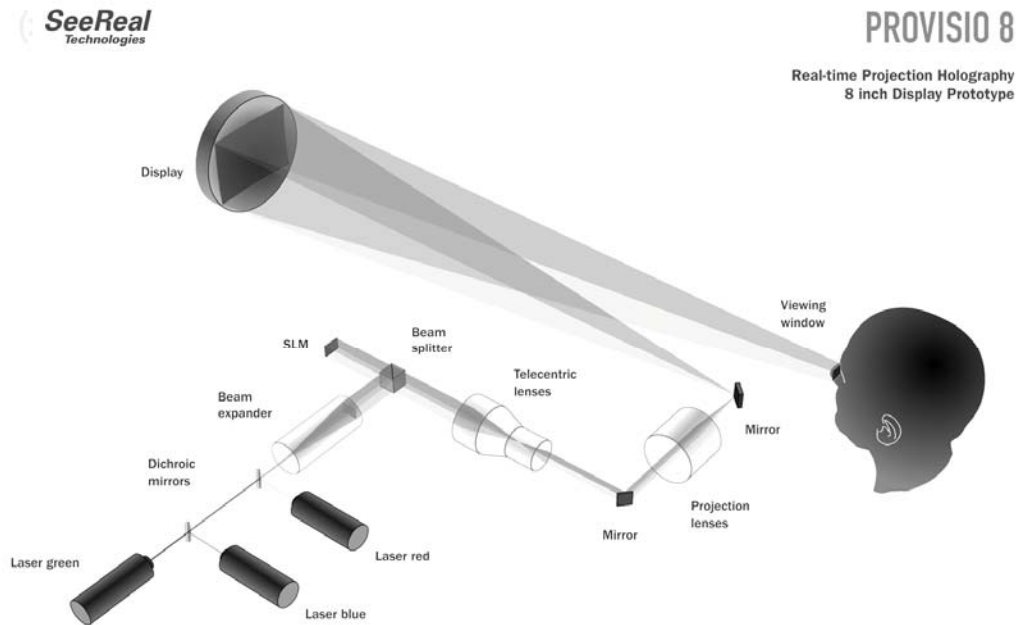


Fig. 3. The 8 inch projection prototype. The setup for one eye is shown. Three laser beams of different color (red, green, blue) are combined by dichroic mirrors. A beam expander is used for illumination of the SLM area. Further components are a telecentric lens system used as filtering unit and a projection lens for imaging SLM to the screen. An observer window is generated.

Light sources

Red, green and blue lasers are used as light sources. The corresponding wavelengths are 635 nm for red, 532 nm for green and 475 nm for blue. The red one is a laser diode, green and blue lasers are of type frequency doubled NdYag. As the observer's eye pupil if located inside the observer window is directly irradiated by a certain amount of laser light it has to be made sure that the intensity in the system in any case is low enough, in order not to cause any damage to the eye. So laser safety issues have been carefully considered in the setup of the prototype. It has been proven that the maximum intensity that the eye may be exposed to in the prototype does not exceed the limit of 30 μW per color which means that there is no danger at all for the user.

Beam expander and dichroic mirrors

The active area of the SLM is about 0,7 inch in diameter. The laser beams have to be expanded at least to this size in order to get a sufficiently uniform illumination over the SLM area. As 3 separate beam expander units would add too much complexity to the system, instead the three beams are superposed first and then a common beam expander for all three of them is used. Superposition of the three beams takes place with 2 dichroic mirrors. Green and blue laser beams are superposed by the one mirror. Afterwards the red beam is added by use of the second mirror.

Light modulator

A very important component of the setup is the SLM. The use of micro display allows for a greater choice between different types of commercially available light modulators compared to a large area display in a direct view setup. A special issue is the existence of pure phase mode SLM, whereas such devices are not yet available for large size displays. But some display types like binary ones have to be excluded: The use of binary holograms is common for example for diffractive elements made by lithography. In case of Fourier holograms for example for beam steering the intended result is a relatively simple kind of 2dimensional intensity pattern in the Fourier plane of the hologram. Then it is possible to get sufficient reconstruction quality with such binary samples.

On the other hand for a reconstruction of a 3 dimensional scene even in case of the observer window type of hologram the requirements for the hologram medium are more advanced. In the observer window intensity and phase values as well have to correspond to the intended wavefront originating from the 3d scene and this wavefront may have somewhat more complicated structure compared to usual DOE tasks. So after doing some simulations we have come to the conclusion that in our case the reconstruction quality of a 3D scene in a holographic display would be significantly deteriorated by use of a binary type hologram medium.

Therefore light modulator types like for example DLP or ferroelectric LC - having only 2 modulation states - were not taken into account. Even a gray scale emulation by time averaging is not suitable for a holographic reconstruction where coherent light is needed. Pulse width modulation techniques used for gray scale emulation in 2d displays would lead to a sequence of mutually incoherent holograms not leading to the desired reconstruction. So a true gray scale type of SLM is needed.

Amongst the commonly used nematic liquid crystal micro display SLM there exist two kinds, transmissive displays usually made as HTPS or LTPS TFT and on the other hand reflective LCoS type displays. A comparison of both types under the special aspect of optical manipulation applications has for example been given in¹⁰, where the conclusions are made in favor of reflective ones.

In our setup preference was given to LCoS type light modulators. One advantage is their high fill factor of 80-90 % which in coherent applications reduces light loss due to higher diffraction orders. In addition high resolution phase modulators are only available as LCoS type. Reflective modulators in general are also faster due to lower cell thickness. Light modulators available from the company HoloEye were used. These modulators have true HDTV resolution i.e. 1920x1080 pixel and exist in 2 versions, one type as amplitude modulator and a corresponding type with similar parameters (i.e. same pixel pitch) as a pure phase modulator making use of the ECB liquid crystal mode.

Both types of light modulators either amplitude or phase were tested as options in the setup. For the amplitude type a detour phase encoding was used¹¹ leading to good reconstruction quality but with relatively low light efficiency. For the phase SLM some kind of two-phase coding¹² was used.

Properties of an HDTV Holoeye phase modulator are discussed in¹³. The type of SLM actually used was an enhanced version of the one described there having the same resolution but smaller pixel pitch and – the main advantage – was operating at larger frame rates. The frame rate of up to 360 Hz allowed for use of time-sequential color for reconstruction of red, green and blue hologram. The 3 laser light sources were synchronized by using a signal from the driver electronics of the LCoS.

Filter unit

For filtering a telecentric lens system was used. The aperture in the filter plane of the telecentric lens was adapted to the size corresponding to the observer window for blue light.

Projection Lens

In order to do the magnified imaging of the SLM on the screen a high quality commercially available photo lens was used. This was the easiest way to achieve good projection quality for a first prototype without sticking too much time into optics design. For improved version a specially adapted optics may be developed.

A further option which was also considered but not realized in the final prototype would be the use of an anamorphic lens as it is commonly found in movie projectors. This would enable us to change the aspect ratio of the screen projection to movie formats. On the other hand – as the projected pixel pitch is related to the observer window size it would have an effect of the ratio observer window height/width, which has to be taken into account in the setup.

Screen

Whereas some other components used in the setup are similar to or may even be found in identical form in a 2d projection unit, the screen shows some major difference in comparison with conventional projection screens. A

projection screen for 2d systems is a plane diffuse medium, in order to spread light over a large observer angle. In contrast to this the holographic projection screen has to maintain the coherence of light, and has to be for example a mirror surface. In addition to this it has to steer light towards the observer window. A focusing means is needed for generating the Fourier transform of the hologram at the intended position of the observer window. In principle some kind of flat screen in combination with a large lens could be used but for a reflecting screen it is easier to combine both features by using a curved mirror.

In our 8 inch prototype a solid type mirror was used. A second prototype was also set up with a 20 inch solid mirror. This mirror was not commercially available but had to be custom designed. Of course for larger prototypes the practical applicability would be limited by the large weight of such a mirror. So an alternative solution may be some kind of lightweight mirror structure similar to those developed for astronomy¹⁴.

As a further option the use of some kind of diffractive mirror structure was taken into account, namely the combination of a flat reflective surface with diffractive lens structures. A flat screen may also be preferable in terms of weight and required space.

In this case the wavelength dependence of diffractive elements has to be taken into account. As the element has to work for three separate laser wavelength but with the advantage that each of them being of narrow width, a sample of a multi order DOE was fabricated acting at a different diffraction order for each laser wavelength. Experimental tests with this DOE showed an acceptable hologram reconstruction. Multi order DOE can also be useful in direct view holographic displays. This is discussed in more detail in a different paper¹⁵.

Holo calculation

Further important components of the setup are an eye finder for detecting the observers current eye position and last but not least the hardware for real time calculation of holograms. Indeed, as the SeeReal's original direct view prototype used single parallax holograms, the 8 inch projection prototype was the first one to be able to demonstrate full parallax encoding. Therefore the SeeReal full parallax real time calculation was tested on this prototype. But as the principles of real time calculation are common to direct view and to projection, they are described elsewhere⁹.

The system was set up for an observer distance of about 130 cm away from the screen.

6 RESULTS WITH 8 INCH PROTOTYPE

The prototype was build up and experimental results of color reconstructions were demonstrated. At first simple geometrical structures were shown to verify accurate reconstruction and depth reproduction.

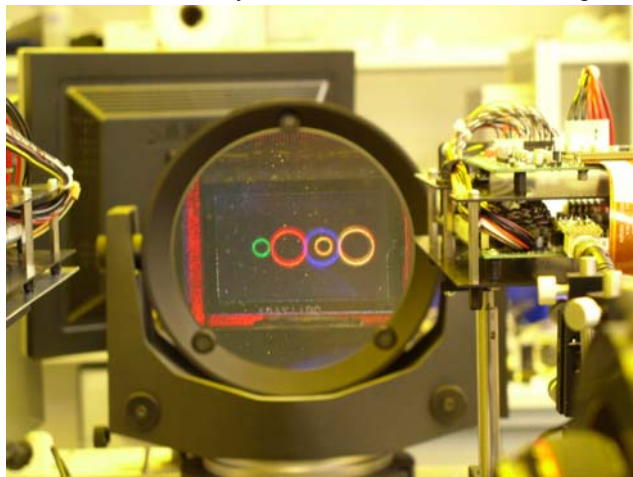


Fig. 4. Camera image taken from a position inside the observer window of one eye looking. Reconstruction of several circles located at different depth positions and being of different color (red green blue and yellow – yellow circles are composed of blue and green reconstruction) The mirror screen has a diameter of 8 inch. The desktop monitor at the background gives an impression of the scale of the reconstruction.

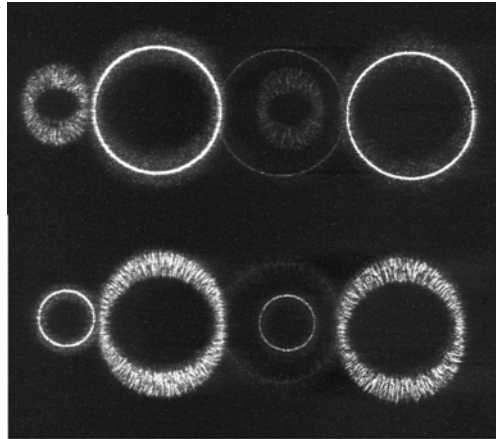


Fig. 5. Same color reconstruction as previous figure (images shot with b/w camera) Different depth of the reconstructed circles is illustrated.. Upper part of the figure: focussing is done on the circles 50 cm in front of the screen. Lower part of the figure: focussing on the circles located 50 cm behind the screen.

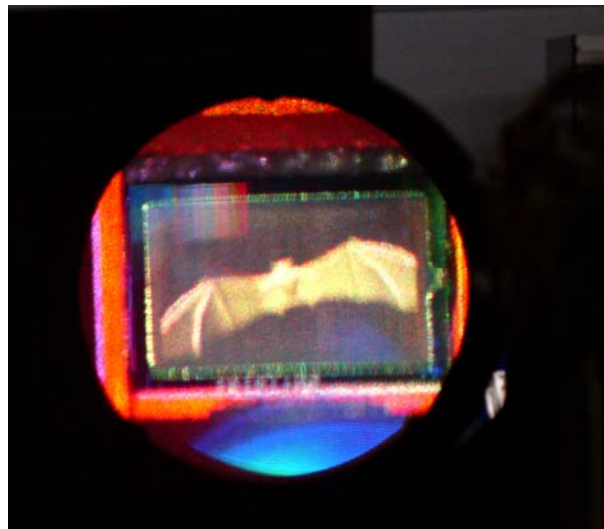


Fig. 6. Color reconstruction of a bat. The hologram was generated from input data 2d + depth map

Figure 5 shows an example of circles at different depth, the camera focusing on part of these circles whilst others are blurred. By comparison with the same camera focusing on real objects – for example a piece of paper with small letters it was confirmed that the reconstruction leads to the intended depth coordinate of the objects. So for example a circle intended to be located 60 cm in front of the screen showed only a deviation of 1-2 cm in its focus.

In addition to these quantitative measurements also holo calculation was done from 2d content + depth map to show the ability to reconstruct complex scenes. A flying bat is shown in figure 7.

7 TRACKING CONCEPTS/ 20 INCH PT

One of the limitations of the 8 inch prototype was that it was designed for almost fixed position of the observer. On the other hand an essential part of the SeeReal holography approach is user tracking, previously already known from autostereoscopic displays. A camera image of the observer is taken, the position of the eye pupil is detected by image processing, and then a tracking system shifts the observer window to the new position, whilst hologram content is updated by real time calculation. In general tracking has to be done for lateral observer movement and for a change in viewer distance (z-tracking) as well.

In the direct view prototype this was for example implemented by light source tracking – electronically shifting the position of the light source array relative to hologram display – and by changing the distance of each pair of light sources for z-tracking. For the projection setup we decided to split up the investigations and therefore tracking was first investigated by means of a separate prototype.

For a projection setup there exist several possibilities for tracking. Light source tracking can in principle be also done there but in case of the setup with laser light sources, mirrors and beam expander was not found to be suitable. Instead a scanner based solution was chosen. The position of the SLM and the light source are fixed. Also the image of the SLM on the screen is not allowed to move. The Fourier transform of the SLM data has to move in order to generate a shift of the viewing window. Therefore in the plane of an intermediate image of the SLM a scanning mirror is introduced. The image of the SLM is thus tilted and the observer window is shifted. This principle is illustrated in figure 7.

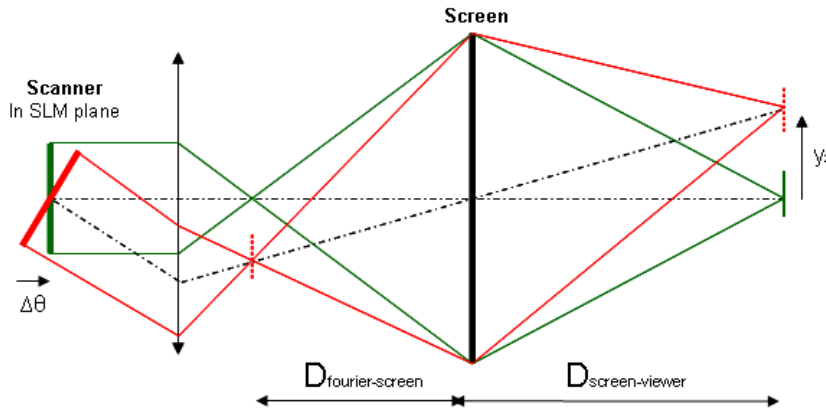


Fig. 7. Principle of the scanner based tracking. Rotation of a scanning mirror causes a movement of the observer window.

For this approach, a large photo-lens between the scanner and the screen is required. Practically to overcome the problem, the photo-lens has been replaced by an elliptical mirror. This elliptical mirror has the property to be stigmatic for two foci points. Thus, whatever the scanning mirror positions the centre of the SLM, is always perfectly imaged on the centre of the screen.

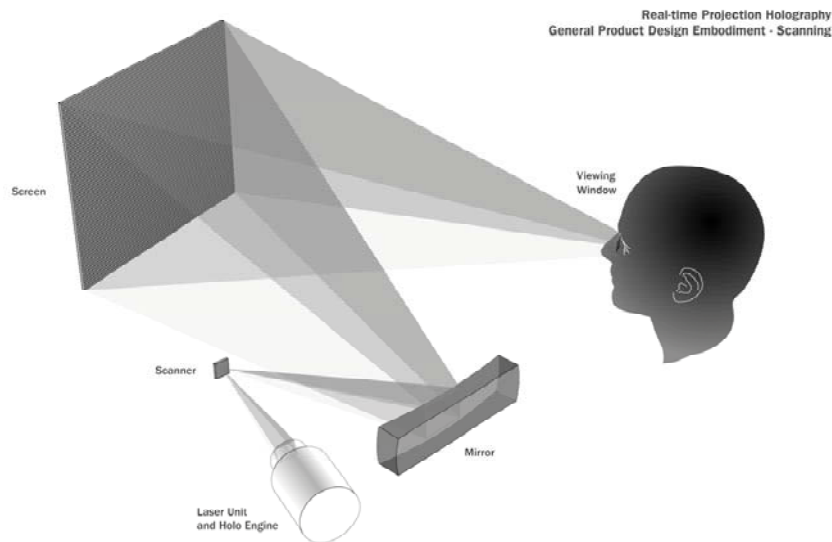


Fig. 8. The setup with the scanner and the elliptical mirror in order to demonstrate the user tracking capabilities of the system.

We developed a 20 inch monochromatic prototype where this scanner tracking was implemented. A 20 inch holographic reconstruction was visible at a distance of only 1 meter from the screen. Demonstration of a tracking range of over 6 inch served as verification of our tracking principle.

8 CONCLUSIONS

It was successfully demonstrated that a projection type holographic displays using the SeeReal observer window approach can be built. With one 8 inch prototype a large scale color holographic display has for the first time been demonstrated. This display was designed for fixed observer position. With another even larger – namely 20 inch - prototype the user tracking capabilities of our projection system were verified.

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