Large real-time holographic displays: from prototypes to a consumer product

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ABSTRACT

Large real-time holographic displays with full color are feasible with SeeReal’s new approach to holography and today’s technology. The display provides the information about the 3D scene in a viewing window at each observer eye. A tracking system always locates the viewing windows at the observer eyes. This combination of diffractive and refractive optics leads to a significant reduction of required display resolution and computation effort and enables holographic displays for wide-spread consumer applications. We tested our approach with two 20 inch prototypes that use two alternatives to achieve full color. One prototype uses color filters and interlaced holograms to generate the colors simultaneously. The other prototype generates the colors sequentially. In this paper we review our technology briefly, explain the two alternatives to full color and discuss the next steps toward a consumer product.

Keywords: 3D display, holographic display, real-time hologram, sequential colors, color filters

1. INTRODUCTION

The interest in displaying 3D information has been growing for several years. There is not only an increasing availability of 3D content but also of 3D displays. 3D displays comprise stereoscopic displays (which include autostereoscopic displays), volumetric and holographic displays. Stereoscopic displays are already commercially available and have reached good image quality regarding for instance resolution, brightness and color reproduction. Holographic displays, however, are still on the level of prototypes.

Stereoscopic displays provide each user with at least two different images of a 3D scene, one image for each eye. Each eye perceives a view of the 3D scene from a different perspective. The human vision system combines these images and thus gets a 3D impression. Multi-view displays which provide more than two images allow for a look-around effect upon user’s movement and increase the viewing region from which the user can see the 3D scene. The different images are displayed on a spatial light modulator (SLM) which in most cases is a LCD. Separation of the images at the eyes is achieved by either spatial or temporal multiplexing.

The general drawback of stereoscopic displays is that the images presented to the eyes are only flat images. Each image shows a different perspective of the 3D scene but is in itself only a flat front view of the 3D scene. This leads to the so-called accommodation-convergence mismatch. The convergence of the eyes is toward the actual distance of the object points in the 3D scene. However, the focus of the eye lenses is always fixed on the SLM surface, independent of the actual distance of the object points. This may lead to eye strain and fatigue and limits the use of stereoscopic displays.

In contrast thereto, holographic displays provide all depth cues that a real 3D scene would generate. Both convergence and eye focus lead to the same depth information as the eye lenses focus on the actual distance of an object point of the 3D scene. This is because a holographic display reconstructs the wavefront that would be generated by a real 3D scene and therefore mimics natural viewing.

Volumetric displays are also capable of providing all depth cues of a real 3D scene. However, the 3D scene is inherently limited to the volume of the display.

There are several prototypes of holographic displays based on a classic approach to holography, using either a high-frequency acousto-optic SLM or a SLM with a large number of pixels, e.g. 15 million pixels or 100 million pixels. The lateral extent of the holographically reconstructed 3D scene is determined by the pixel pitch of the SLM and is limited to approximately 10 cm for these prototypes.
We developed an alternative approach to holographic displays which overcomes the barrier of the 3D scene size being determined by the pixel pitch of the SLM\(^5\). Prototypes based on this technology were successfully presented at several international exhibitions (SID 2007, FPD International 2007 and Finetech 2008). In this article we will review our technology briefly and explain our solutions for full-color displays. Full-color is a feature that is mandatory for the progress from prototypes to a consumer product.

## 2. TRACKED VIEWING-WINDOW TECHNOLOGY

### 2.1 Viewing window and sub-hologram

The fundamental difference between conventional holographic displays and our approach is in the primary goal of the holographic reconstruction. In conventional displays, the primary goal is to reconstruct the 3D scene. This 3D scene can be seen from a viewing region that is larger than the eye separation.

In contrast thereto, in our approach the primary goal is to reconstruct the wavefront that would be generated by a real existing 3D scene at the eye positions. The reconstructed 3D scene can be seen if each observer eye is positioned at a virtual viewing window (VW). A VW is the Fourier transform of the hologram and is located in the Fourier plane of the hologram. The size of the VW is limited to one diffraction order of the Fourier transform of the hologram.

![Side view of a holographic display with lens, SLM, one object point and observer eye. The left drawing shows the wavefront information that is generated in the conventional approach (red) and the essential wavefront information (green) that is actually needed at a virtual viewing window (VW). The essential wavefront information is encoded in a sub-hologram (SH) on the SLM. The dashed blue lines indicate a frustum in which the object points can be located. The two right drawings illustrate a VW that is tracked to the observer eye. The illumination of the SLM was omitted in these drawings for simplification.](image)

Fig. 1 illustrates our approach and shows a Fourier transforming lens, a SLM and an eye of an observer. Coherent light transmitted by the lens illuminates the SLM. The SLM is encoded with a hologram that reconstructs an object point of a 3D scene. A 3D scene with only one object point and its associated spherical wavefront is shown. It is evident that more complex 3D scenes with many object points are possible by superposing the individual holograms.

The conventional approach to holographic displays generates the wavefront that is drawn in red. The wavefront information of the object point is encoded on the whole SLM. The modulated light reconstructs the object point which is visible from a region that is much larger than the eye pupil. As the eye perceives only the wavefront information that is transmitted by the eye pupil, most of the information is wasted. Therefore, much effort is done to project light into regions where no observer eye is.
In contrast thereto, our approach limits the wavefront information to the essential information. The correct wavefront is provided only at the positions where it is actually needed, i.e. at the eye pupils.

Fig. 1 shows a virtual VW which is positioned close to an eye pupil. The wavefront information is encoded only in a limited area on the SLM, the so-called sub-hologram (SH). The position and size of the SH is determined geometrically by projecting the VW through the object point onto the SLM. This is indicated by the green lines from the edges of the VW through the object point to the edges of the SH. Only the light emitted in the SH will reach the VW and is therefore relevant for the eye. Light emitted outside the SH and encoded with the wavefront information of the object point would not reach the VW and would therefore be wasted. This is indicated in Fig. 1 by the green spherical wavefronts for the essential information and the red spherical wavefronts for the wasted information. The observer will not notice that the wavefront information outside the VW is not present or not useful as long as each eye pupil is in a VW.

The VW has to be at least as large as the eye pupil and at most as large as a diffraction order in the observer plane. This ensures that light from only one diffraction order will reach the VW. Light emanating from other diffraction orders of the reconstructed object point is outside the VW and is therefore not seen by the eye. The size of the SH depends on the distance of the point from the SLM. The VW has a typical size of several millimeters.

Our displays differs from prior art not only in hologram encoding but also in the optical setup. Prior-art displays reconstruct the 3D scene around the Fourier plane and provide viewing regions behind the Fourier plane. Our displays provide VWs for observers in the Fourier plane. The 3D scene is located between the Fourier plane and the SLM or behind the SLM.

The essential idea of our approach is that for a holographic display the highest priority is to reconstruct the wavefront at the eye positions that would be generated by a real existing 3D scene and not the to reconstruct the 3D scene itself.

2.2 Required pitch of the SLM

For conventional holographic displays, the reconstructed 3D scene is essentially the Fourier transform of the hologram. The diffraction angle of the SLM determines the size of the reconstructed 3D scene and hence a small pixel pitch is needed. A large lateral size of the 3D scene (e.g. 20 inch) would require a pixel pitch of the order of 1 µm.

The requirements on the pitch of the SLM are significantly lessened by our approach. The VW is the Fourier transform of the hologram. The diffraction angle of the SLM determines the size of the VW. A moderate pixel pitch of 50 µm generates a VW with lateral size of 20 mm at a distance of 2 m. These are typical values for a holographic display for TV applications. The size of the reconstructed 3D scene is not limited by the pixel pitch but by the size of the SLM. The 3D scene can be located anywhere in a frustum defined by the VW and the SLM. This frustum is indicated by the dashed blue lines in Fig. 1. The 3D scene can be located in front of and behind the SLM.

Therefore, our approach makes holographic displays for large 3D scene reconstructions feasible.

2.3 Observer tracking

The display is equipped with an eye position detector and a real-time tracking system. The eye position detector and the tracking system always locate the VWs at the observer eyes. Tracking is illustrated in the two right drawings of Fig. 1. The tracking system adapts the SLM illumination and the SH location on the SLM to the positions of the observer eyes.

There are two alternatives for the tracking system:

- Light source tracking
  Shifting the position of the light source also shifts the position of the VW. The position of the light source does not have to be shifted mechanically. A light source may be an activated pixel in an additional LCD that is illuminated by a homogenous backlight. By activating a pixel at the desired position on the LCD the light source can be shifted electronically without mechanical movement.

- Beam-steering element
  With a beam-steering element after the SLM the optical path from the light source to the SLM can be kept constant. The beam-steering element deflects the light after the SLM and directs the light toward the observer eyes. As an example, the beam-steering element may be based on electro-wetting. Two non-mixable liquids with different refractive indices are in a cell with electrodes at its walls. Applying a voltage to the electrodes
determines the interface angle between the liquids and thus the deflection angle of the light passing the interface.

3. FULL-COLOR HOLOGRAPHIC DISPLAY

3.1 Full-color holography in general

As holography is based on diffraction and as diffraction is wavelength-dependent, the 3D scene has to be separated in its color components. Usually, these are red, green and blue. Three holograms are computed (one for each color component) and the 3D scene is reconstructed using three light sources with the corresponding wavelengths. There are several methods to combine the three holograms and the three light sources, for instance:

- Spatial multiplexing
  The red, green and blue holograms are spatially separated. For instance, they may be displayed on three separate SLMs that are illuminated by red, green and blue light sources. An arrangement of dichroic beamsplitters combines the output of the SLMs. The optical setup is bulky, above all for large displays.

- Temporal multiplexing
  The red, green and blue holograms are displayed sequentially on the same SLM. The red, green and blue light sources are switched in synchronization with the SLM. Fast SLMs are required to avoid color flickering.

3.2 Components of our monochrome and full-color prototypes

Our current prototypes are improved versions of our first monochrome 20 inch holographic display described earlier. They are based on the same principles but are built using better components and are less bulky. The monochrome and the two full-color versions differ only in few components. Therefore, a common description will suffice to explain the fundamentals of the three versions. We already built a full-color 8 inch holographic display that uses small projection micro displays which are optically enlarged, as described earlier.

Fig. 2. Setup of the 20 inch prototype. The components are (from left to right): LED backlight, shutter display, Fourier lenticular, SLM and beam-splitting lenticular. The inset shows two interlaced holograms on the SLM that are separated by the beam-splitting lenticular in order to generate two VWs.
Fig. 2 shows the setup of the 20 inch prototype. The components are LED backlight, shutter display, Fourier lenticular, SLM and beam-splitting lenticular (from left to right).

The LED backlight consists of red, green and blue high-brightness LEDs with wavelengths 627 nm, 530 nm and 470 nm. The spectral linewidth (FWHM) $\Delta \lambda \approx 30$ nm provides sufficient temporal coherence.

The SLM used in this prototype is a standard monochrome LCD with 20 inch diagonal and 15 million amplitude-modulating pixels. The pixel pitch is 156 $\mu$m horizontal and 52 $\mu$m vertical. The hologram was encoded in the display by detour-phase encoding using three pixels to represent one complex number. The size $w$ of the VW is one third of one diffraction order and is given by $w = \lambda / d/p$. This results in a VW size $w = 6$ mm with the smallest wavelength $\lambda = 470$ nm at an observer distance $d = 2$ m and a pitch $p = 156$ $\mu$m. The hologram is a vertical-parallax-only hologram with holographic reconstruction in the vertical direction. The vertical VW size $w = 6$ mm is sufficient for an eye pupil and facilitates eye focusing to a reconstructed object point.

A lenticular comprising approximately 60 horizontal cylindrical lenses is used, instead of a single bulky Fourier-transforming lens. Each cylindrical lens is illuminated by a horizontal line light source. A line light source is comprised of activated pixels in an additional LCD which serves as a shutter display and which is illuminated by the LED backlight. The display with the encoded hologram is illuminated by the multitude of light sources, and each lens performs an optical Fourier transform of a part of the hologram in the vertical direction. As the light sources are mutually incoherent the eyes see a reconstructed 3D scene that is composed of mutually incoherent partial 3D scenes. This may lead to brightness inhomogeneities that can be compensated in the hologram calculation.

Two VWs, one for each eye, with a horizontal separation of approximately 65 mm are generated by spatial multiplexing. Two holograms are interlaced in the display. A lenticular is used as a beam-splitting element and projects light from one hologram to the left eye and light from the other hologram to the right eye. This technique is well known from stereoscopic displays. In our case, each eye sees a holographic 3D scene reconstruction that is generated by its own hologram.

An eye position detector controls the positions of the VWs in real time. Vertical and axial tracking is achieved by adapting the positions of the line light sources on the shutter display. Horizontal shifting of the hologram content on the SLM facilitates horizontal tracking.

### 3.3 Prototype with temporal color multiplexing

The colors are displayed sequentially for temporal color multiplexing. The SLM sequentially displays the holograms of the red, green and blue 3D scene components and the backlight is switched between red, green and blue LEDs. Both processes are synchronized.

However, two obstacles have to be taken into account to achieve good reconstruction quality:

- The pixels of the SLM have a finite response time. For a LCD, this is the time the liquid crystals need to align to the electric field applied to the pixel cell. The LCD panel which we use as SLM stems from a medical LCD and has a long response time $T_{\text{on}} + T_{\text{off}} = 30$ ms.
- The pixels do not switch simultaneously across the SLM as the pixels are addressed in columns and rows. The rows of the SLM are addressed sequentially, with one frame period needed from the first to the last row. As a consequence, there is a time lag of up to one frame period across the SLM.

Both effects have to be taken account as each part of the hologram has to be illuminated with the corresponding wavelength. For instance, if SLM and backlight were switched from red to blue simultaneously, the last rows of the SLM would still display the red hologram when the backlight is already switched to blue. Therefore, we used a scanning backlight and a time lag between switching the SLM and the backlight.

Fig. 3 illustrates this process. The top graph shows the states of the SLM rows versus time and the bottom graph the states of the backlight rows versus time.

The gradual color transition along the time axis of the SLM graph illustrates the finite response time after switching from a hologram of one color component to the hologram of the next color component. There is no sharp transition from one hologram to the next hologram but an intermediate interval in which the pixels of the SLM transit to the next state. The color transition along the row axis of the SLM graph illustrates that the SLM is addressed row-by-row. At a point in time...
at which the last row has just received the data of the current frame the first row will already receive the data of the next frame. As an example, at the second dotted vertical line, the last row has just settled to the red hologram whereas the first row already starts to transit to the green hologram.

The intermediate states are indicated by the slanted gradual color transition. At these points in time, the state of the respective SLM pixel is undefined, and illumination by the backlight has to be avoided. Therefore, we built a scanning backlight in which the rows of LEDs are grouped in 16 groups. Switching of these groups is illustrated in the backlight graph of Fig. 3. These groups are switched on and off sequentially such that the corresponding parts of the hologram are only illuminated if its pixels are in a settled state of the associated color.

Fig. 3. State of SLM rows (top) and backlight rows (bottom) versus time. The SLM graph illustrates the effect of finite response time and row-by-row addressing of the SLM after switching from one hologram to the next hologram. The backlight graph shows delayed and row-by-row switching of the backlight to compensate these effects.

A complete cycle comprises three frames with colors red, green and blue and three intermediate transition frames. As the frame rate of the SLM is 60 Hz, the full-color frame rate is 10 Hz. The human vision perceives a full-color holographic reconstruction, albeit with color flickering. Color flickering will disappear and a steady reconstruction will be visible with availability of faster SLMs.

### 3.4 Prototype with spatial color multiplexing

A display with spatial color multiplexing shows the three backlight colors and the three holograms for red, green and blue color components simultaneously. A large holographic display using three separate SLMs for the three holograms and dichroic beamsplitters to combine the light would be too bulky. Rather, the three holograms are interlaced on the same SLM. A color filter is used to achieve that each hologram is illuminated with its associated wavelength only.

Six holograms have to be interlaced on the SLM: three red, green and blue holograms that generate the VW for the left eye \( \text{VW}_L \) and also three holograms to generate \( \text{VW}_R \). A beam-splitting lenticular is used to separate the light for \( \text{VW}_L \) and \( \text{VW}_R \). Color filters are used to separate the wavelengths.

Fig. 4 illustrates top views of two possible arrangements of color filters. The left arrangement uses color filters that are integrated in the SLM pixels. One lens of the beam-splitting lenticular is assigned to two pixels of the SLM. The light of all left pixels at the lenses coincides in the observer plane and generates \( \text{VW}_R \). Vice versa the right pixels generate \( \text{VW}_L \). The color filters are arranged in columns such that each column of the filter extends over two columns of the SLM, as illustrated in the left graph of Fig. 4.

Such an arrangement of color filters integrated in the SLM pixels and two neighboring pixels having the same color is not commercially available. Standard LCD panels have color filters with color changing from pixel to pixel. An external color filter laminated on the cover glass of the panel would have a disturbing separation between pixel and color filter.
Fig. 4. Top view of an arrangement of color filters in a holographic display with spatial color multiplexing. The left graph shows color filters integrated in the SLM pixels (SLM + CF) and the right graph separate color filters (CF). The graphs show three lenses of the lenticular (L) that splits the light to generate left viewing window (VWₗ) and right viewing window (VWᵦ). For simplification, only the light illuminating VWᵦ is shown and the light illuminating VWₗ is omitted. The light sources and the Fourier-transforming lenses are not shown.

Therefore, in our prototype we used the arrangement illustrated in the right graph of Fig. 4. The color filters are attached directly to the structured surface of the beam-splitting lenticular. This arrangement avoids a disturbing separation between lenticular and color filter and facilitates tracked VWs in the same way as with a monochrome display. The functional principle is analog to that of the arrangement in the left graph of Fig. 4.

3.5 Improvements toward a product

Fig. 5 shows a picture of our full-color holographic display. The dinosaur is only an illustration as a high-quality photograph is difficult to achieve due to limited brightness and lens aperture. The aperture of the camera lens would have to be within a VW with a size of 8 mm.

Our two holographic displays reconstruct full-color 3D scenes with a diagonal of 20 inch. User tracking is achieved with an eye position sensor and a tracking system that are integrated in the display housing. The holograms are calculated in real time with 60 frames per second on two linked graphics cards of a PC. This is a prototype solution only, integration of hologram calculation on a compact dedicated board with FPGA and ASIC is on progress.

Both prototypes were built with commercially available components and demonstrate that our approach to holography can be extended to full-color displays. The usage of available components leads to limitations of the prototypes that can be overcome by designing improved components for the application in a future mass-market product:

- Our prototype with temporal color multiplexing has a full-color frame rate of only 10 Hz. This leads inevitably to strong color flickering perceived by human vision. The low frame rate is caused by the slow LCD panel which we have to use. Large high-resolution monochrome panels are currently used only in medical displays and are therefore not optimized with respect to response time and frame rate. On the other hand, there are LCD panels for TV applications on the market with frame rates of 180 Hz and higher. The technology for fast LCD panels exists and has only to be applied to high-resolution monochrome panels. This would facilitate full-color holographic displays without color flickering.

- The prototype with spatial color multiplexing has color filters attached to the beam-splitting lenticular. A display manufacturer could easily alter the manufacturing process of color filters integrated in the SLM pixels to our required configuration. Such color filters have to be non-scattering in order to preserve coherence of light.

- Furthermore, both prototypes are using an amplitude-modulating SLM to encode the hologram. This is possible, albeit with a low diffraction efficiency of the order of 1% and therefore low brightness. A phase-modulating
SLM would increase the diffraction efficiency and hence the brightness by approximately one order of magnitude. Small projection displays are already available with phase modulation. It would be a small step for a display manufacturer to apply this LC configuration to larger displays in order to get a large phase-modulating SLM.

The required alterations to existing LCD panels are moderate and are justified as the display manufacturers get access to the new market of full-color holographic displays.

![Figure 5](image_url)  
Fig. 5. Picture of our full-color holographic display with a screen diagonal of 20 inch. The dinosaur is only an illustration.

4. CONCLUSIONS

After presentation of our monochrome display in 2007 we now reached a further milestone on the roadmap toward a consumer product. We demonstrated that a full-color holographic display with 3D scene size of 20 inch is possible with existing technology.

This success is made possible by our new approach to holography. A virtual viewing window is located at each eye of an observer through which the observer sees the 3D scene. The relevant information is present in these viewing windows only. The viewing windows are tracked to the observer eyes in real time. This approach saves 3 or 4 orders of magnitude of the SLM resolution and computation power compared to conventional holographic displays and makes large real-time holographic 3D scene reconstructions possible.

We demonstrated that full color can be achieved by two alternatives:

- The colors may be generated sequentially. The holograms for the red, green and blue color components and the backlight colors are switched synchronously. A sophisticated control of the backlight compensates the delayed and inhomogeneous response of the SLM. This temporal color multiplexing requires fast SLMs in order to avoid color flickering and color breakup.

- Spatial color multiplexing uses color filters. A prototype arrangement has the color filters on the beam-splitting lenticular whereas color filters integrated in the SLM pixels would be the solution for a product. This alternative requires a resolution of the SLM that is higher than with sequential colors, but is content with a lower SLM frame rate. The required SLM resolution already exists in available LCD panels.

The required amendments to existing LCD panels are moderate. Faster LCD panels with higher resolution are emerging more and more on the market as there is an increasing demand of such panels for TV applications.
Our approach to real-time holographic displays is a key step toward wide-spread application of 3D displays in high-end professional as well as in consumer markets. Holographic displays show no accommodation-convergence mismatch that is inherent in stereoscopic displays. This mismatch may cause less viewing comfort and will hinder the general use of stereoscopic displays for consumer applications. The 3D scene depth of stereoscopic displays has to be limited in order to keep this mismatch at an acceptable level. Only holographic displays can show natural 3D scenes with unlimited depth. Therefore, we consider holography as the preferred option for 3D displays. Our full-color real-time holographic displays demonstrate that holography is feasible for wide-spread application with existing technology.

REFERENCES