Hologram Display - Principle, 3-dimensional Representation, and Sampling

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Abstract

This paper presents the system and realization concept of a 3D color display offering a multiple of depth levels in front of and behind the display screen itself. These new display features will be achieved by an arrangement of lenticular glasses, color and brightness filters and a high resolution binary liquid crystal display being writable by laser beams and being erasable by electrical fields. The LC-layer can be substituted by a cheap image-coded black/white film showing a 3D-photo. First models of 3D color pictures have been produced up to a size of 25 x 20 inch² on a photo color display.

First prototypes of 3D Photo Displays have been presented at the last ICCE 99 in L.A. and at the Hannover fair 2000. These displays use lenticular glass and offer up to 100 different views of objects or landscapes to the user. It looks like a hologram but it offers full color quality. Chapter 6 of this contribution describes the mathematical principles and the necessary filtering operations to present the 3-dimensional objects correctly. The filtering operations which verify the described theory have been implemented and used for the 3D image generation.

1. Introduction

Widely used 3D design software, 3D mice, games, and graphic processing power is available on the market. But no user really can see the objects which he has designed or which he plays with, in a natural three-dimensional manner. There exist commercial components like shutter glasses, polarization glasses, head tracker controlling the viewing directions of objects and the autostereoscopic view of only one user. All these products are advantageous when real time processing can be used, but they do have the disadvantage to offer only two views of the objects simultaneously, one view for the right eye and the other for the left eye. Consequently, the focal point and the parallax crossing point defer from one another. This can cause headache when applied for a longer period e.g. in 3D cinemas. The new approach to improve the 3D vision is to produce a multiple of views simultaneously and to distribute them optically in the correspondent directions. This article will show how up to 128 different views can be produced by a 3D color display which distributes the optical views like a hologram. Therefore, it has been called also "Ho-
2. Specified features

It is planned to develop a 3D-color display which will have very high quality 3D pixel resolutions up to 1280 x 1024 x 128 (width, height, depth). Within a predefined space in front of the screen it offers to observers nearly the whole three-dimensional perception quality of human eyes. Thus a maximum of half a GByte has to be coded and written for one complete 3D-image frame. Therefore, a writing time over 10 minutes must be taken into account at first. But later on laser diod-arrays will be used to increase the writing speed dramatically. Once a LC-pixel is set, it holds the information for years without energy consumption. The LC-pixel can be reset into the original transparent state. Using black/white pixel sizes of $4 \mu m \times 4 \mu m$ a screen size of 25 inch x 20 inch will be achieved.

3. Description of the 3D Principle

To present high quality 3D images a lot of different views from an object or a landscape must be stored in each 3D-pixel to get a continuous sequence of views while the head of an observer carries out horizontal movements - of course within a predefined space in front of the display. Normally, it is not essential to get different views by vertical movements of the head. Therefore, this display takes into account only horizontal 3D-effects which result into a higher number of different horizontal views: over 128 within each pixel. Thus, continuous view transitions are offered to an observer.

Figure 1 gives an overview of the principle function of the 3D-display. The front of the display screen consists of a vertical lenticular glass containing 1280 cylindrical lenses having its focus on the binary LC-layer. Between the screen and the lenticular glass there is inserted a color filter having got horizontal RGB (red, green, blue) stripes and brightness masks consisting of different gray stripes within each color stripe. The liquid crystal can be locally (on $\mu m$-areas) set into two states: transparent or disperse.

![Fig.1: Viewing range and construction of the "Kassel Display"](image)

4. 3D Pixel Structure

Each 3D pixel on the screen consists of a multiplicity of color slit pixels. Each slit is a pixel of image being seen of the corresponding viewing direction. Fig. 2 shows such a pixel arrangement. In fig. 2 the light ray flow of the first ($n=1$) and the last ($n=100$) viewing direction is drawn. Behind the cylindrical lenses the light is focused on a small slit of some $\mu m$. On this slit, the color pixel is composed by the three color components red (R), green (G), blue (B). A fourth black (K) stripe is optional (it will not be needed for a pure 3D photo display). And each color component can be set on a certain number of brightness steps, say 64 or 128 depending on the smallest subpixel size and the number of brightness stripes into which each color stripe is subdivided. The fig. shows two brightness stripes e.g. R1 and R2. On a photo display with a 3D pixel size of $500 \times 500 \mu m^2$, for example, the
brightness stripes can carry 25 subpixels, from which a maximum of 24 can be used, because between different stripes the transient subpixels should not be used. This is done to allow mechanical small tolerances without touching the picture quality. In this case $24 \times 24 = 576$ brightness steps can be achieved in maximum. All together one 3D pixel contains $3 \times 2 \times 24 \times 100 = 14400$ binary subpixels of the size $500 \times 500 \mu m^2$, which can be used that means which can be set black or white.

The back light coming from the upper side is absorbed behind transparent regions or distributes light in all directions where the LC is dispersed. The on-switching of the LC states is locally done by laser rays and the off-switching is done more regionally by electrical fields. The laser beams emitted from the lower side horizontally from the back side.

![Fig.2: 3D pixel arrangement](image)

5. Modularity

Sometimes it is more comfortable to produce a higher quantity of a small component than to make a big component needing a higher precision. This holds for the laser writing unit (2) in Fig. 3: It is easier to focus the laser beam on small areas than on a big one; and it helps to increase the writing speed since the lasers can work in parallel. A further possibility to increase the writing speed even more is to develop special laser arrays having integrated deflection devices and high frequency modulators. The adjustment of neighbored laser units will be done by special controllers in combination with an adaptive feed back controller. The feed back signal is measured by optical mini-diodes being placed on the back of the liquid crystal at the black stripes of the color mask.

![Fig.3: Hologram monitor modul using a liquid crystal laser display (LCLD) – outlook and modular construction](image)

The binary display can achieve a resolution down to $4 \mu m$. Thus the high precision lenticular lenses of $500 \mu m$ width can focus out 125 different views depending on the eyes positions.

6. 3D Projection

6.1 Optical principle

The focus of the lenses of the lenticular glass meets the plane, in which the digitally written black-white film or the liquid crystal layer is situated. Due to the high writing resolution of 5080 dpi, up to 100 different views of objects can be emitted over 100 neighbored ray angles. Geometrically, for each pixel a fan projection has to be calculated over a full fan angle of $2\beta$. This angle $\beta$ depends on the pitch $LS_{pitch}$ of the
lenticular lenses, the focal depth point \( R_{\text{focus}} \), and the light index of glass \( N \) (e.g. \( N=1.5 \)). The horizontal pitch \( F_{\text{pitch}} \) on the focal plane is a little bit larger than that of the lenses itself.

\[
F_{\text{pitch}} = \frac{L_{\text{S pitch}}}{1 + R_{\text{focus}} / D_{\text{obs}}} \quad (1)
\]

where \( D_{\text{obs}} \) denotes the optimal distance of the display screen from the observer's eyes, being equal to the distance between the z-position of lenticular plane and the z-position of the observer. The half fan angle \( \beta \) is given by the following function:

\[
\beta = \arctan \left( \frac{F_{\text{pitch}} / N}{2 / R_{\text{focus}}} \right) \quad (2)
\]

For the system presented the following full fan angle is realized: \( 2\beta = 19^\circ \). The number of views \( N_{\text{view}} \) is distributed over the fan angle \( 2\beta \). Therefore the following view density at the observer distance \( D_{\text{obs}} \) from the screen is achieved:

\[
\Delta X_{\text{obs}} = \frac{2 \tan(\beta)}{D_{\text{obs}} / N_{\text{view}}} \quad (3)
\]

For \( N_{\text{view}}=100 \) this density step is \( VD=0.19 \) per view. For each view point the image can be represented by a fan projection on the focal plane of the screen. Altogether a number of \( N_{\text{view}} \) (=100) fan projections have to be carried out.

Fig. 4 shows the relationship of fan angle, lense focus, pitches and optimal planned observer distance from the screen.

Fig. 4: Observer positions: viewing angles, full fan angle with respect to lenticular pitch

Fig. 5: Fan projection onto the screen; sampling grid and 3D resolution

Fig. 5 shows the fan projection for two special eye positions: the right view center and the left view center, being situated in the z-plane of the observer \( z=Z_{\text{obs}} \). The screen is placed in the z-plane \( z=Z_{\text{screen}} \). The pixels on the screen, on which the objects are projected, have the distance \( L_{\text{S pitch}} \). This pitch is given by the width of the screen \( SC_{\text{width}} \) divided by the number of horizon-
tal pixels per view: \( N_{\text{pitch}} \)

\[ L_{\text{pitch}} = \frac{S_{\text{width}}}{N_{\text{pitch}}} \]  

(4)

### 6.2 Image resolution

Normally, the vertical pixel pitch is equal to the horizontal pixel pitch: \( L_{\text{pitch}} = P_{\text{pitchv}} \). The achievable vertical and horizontal object resolution are dependent from depth positions of objects to be represented by the screen - according to the fan projection, shown in fig.5:

\[ \Delta X_{\text{obj}} = \Delta Y_{\text{obj}} = \frac{(Z_{\text{obj}} - Z_{\text{obs}})}{L_{\text{pitch}}/(Z_{\text{screen}} - Z_{\text{obs}})} \]  

(5)

The possible depth resolution of the objects depends in addition from the horizontal distance of the viewing centers, say distance of the two watching eyes: \( D_{\text{eye}} \). The smallest sampling angle might be denoted by \( \Delta \beta \): It is slightly dependent on the angle \( \beta \) itself because \( \Delta X_{\text{obs}} \) is constant.

\[ \Delta \beta = \frac{\Delta X_{\text{obs}} \cdot \cos(\beta)}{Z_{\text{screen}} - Z_{\text{obs}}} \]  

(6)

Let \( k \) be the number of views between the eyes. Then the eye distance corresponds to the sampling angles as follows:

\[ D_{\text{eye}} = k \cdot \Delta X_{\text{obs}} \]  

(7)

where a symmetrical eye position is assumed.

With respect to the two projections centers the following depth sampling planes \( Z_{\text{sp}}(k,i) \) for objects are given:

\[ \left[ Z_{\text{obs}}(i,k) - Z_{\text{screen}} \right] \]

\[ = i \cdot L_{\text{pitch}} \cdot \left[ Z_{\text{obj}}(i,k) - Z_{\text{obs}} \right] / D_{\text{eye}} \]  

(8)

Let be the sampling distances on the screen \( \Delta X_{\text{screen}} = L_{\text{pitch}} \) and those at the eye plane of the observer \( \Delta X_{\text{obs}} \). Then (8) results into the following equation:

\[ Z_{\text{obj}}(i,k) = \frac{Z_{\text{screen}} \cdot k \Delta X_{\text{obs}} - Z_{\text{obs}} \cdot i \Delta X_{\text{screen}}}{k \Delta X_{\text{obs}} - i \Delta X_{\text{screen}}} \]  

(9)

### 6.3 Sampling distances

The z-sampling distance for objects \( \Delta Z_{\text{obj}} \) is given by the difference

\[ \Delta Z_{\text{obj}}(i,k) = Z_{\text{obj}}(i + 1,k) - Z_{\text{obj}}(i,k) \]  

(10)

For simplicity let us use now a coordinate system for which the observer's z-position is zero: \( Z_{\text{obs}} = 0 \). With respect to the fan projection the viewing center of the observer might be:

\[ V = (X_{\text{obs}}, Y_{\text{obs}}, 0) \]  

(11)

The sampling positions of the screen are given by:

\[ S(i_x, i_y) = (i_x \cdot \Delta X_{\text{screen}}, i_y \cdot \Delta Y_{\text{screen}}, Z_{\text{screen}}) \]

with normally

\[ \Delta X_{\text{screen}} = \Delta Y_{\text{screen}} = L_{\text{pitch}} \]  

(12)

The sampling z-planes for objects are derived from (9) by

\[ Z_{\text{obj}}(i_z) = \frac{Z_{\text{screen}} \cdot D_{\text{eye}} - i_z \cdot \Delta X_{\text{screen}}}{D_{\text{eye}} \cdot i_z \cdot \Delta X_{\text{screen}}} \]

with

\[ i_{\text{max}} < i_z < \frac{D_{\text{eye}}}{\Delta X_{\text{screen}}} \]  

(13)

The sampling coordinates for the objects to be projected on the screen pixels are given by
The equivalent equation holds for $Y_{obj}$:

$$y_{obj}(i_z; i_y) = y_{obs} + \frac{Z_{obj}(i_z) \cdot (i_y \cdot \Delta Y_{screen} - y_{obs})}{Z_{screen}}$$ (151)

The sampling distances $\Delta X_{obj}$, $\Delta Y_{obj}$, $\Delta Z_{obj}$ are given as follows:

$$\Delta X_{obj}(i_z) = \frac{\Delta X_{screen} \cdot Z_{obj}(i_z)}{Z_{screen}}$$ (2)

$$\Delta Y_{obj}(i_z) = \frac{\Delta Y_{screen} \cdot Z_{obj}(i_z)}{Z_{screen}}$$ (17)

$$\Delta Z_{obj}(i_z) = Z_{obj}(i_z + 1) - Z_{obj}(i_z)$$

$$= Z_{screen} \cdot \frac{\Delta D}{(1 \cdot (i_z + 1) \cdot \Delta D) \cdot (1 + i_z \cdot \Delta D)}$$ (18)

with $\Delta D = \frac{\Delta X_{screen}}{D_{eye}}$

**6.4 The static object resolution**

These three equations show that the allowed sampling distances of all three directions are depth dependent. The depth sampling index is given by $i_z$. If three-dimensional objects or their surfaces are given with respect to a equidistant sampling coordinates or constant Nyquist frequencies. These object information datas must be filtered and resampled. Therefore the necessary filtering operations will be derived below.

Fig.6: Functional layers of the hologram display with laser written liquid crystal

The sampling resolutions given by equations (16), (17), (18) can be achieved as long as the lenticular focus line is smaller than the horizontal subpixel width of one image view on the focal point plane (cf. fig. 6). This view-pixel width is given by (cf. equ.(1))

$$\Delta X_{view} = \frac{F_{pitch}}{N_{view}}$$ (19)

This highest depth dependent 3D resolution is valid for a fixed observer position. Therefore the resolution of objects given by equ. (16) to (18) is called the static resolution. In case the observer makes a horizontal movement there has to be taken into account another resolution scale which is described in the following.

The observer sampling point distance shown in fig. 4 is given by $\Delta X_{obs}$ (equ. (3)). The x-positions of the viewing point might be given by

$$X_{view}(i) = i \cdot \Delta X_{view}, \quad I_{min} < i < I_{min} + N_{view}$$ (20)
Let now the viewing position move

\[ X_{\text{view}} = (i - 1/2) \cdot \Delta X_{\text{view}}; \quad X_{\text{view}} = (i + 1/2) \cdot \Delta X_{\text{view}} \]  

(21)

In the ideal case of a highest matching optical focus no changing of views happens. But

\[ \Delta X_{\text{obj}}(z) = \Delta X_{\text{screen}} \cdot \frac{z}{Z_{\text{screen}}} \quad \text{and} \]  

(24)

crossing the point \( X_{\text{view}}(i+1/2) \) the neighboured view appears. Consequently the objects structure jumps into the z-plane to the correct position. This jumping step is given by

\[
\Delta X_{\text{objjump}}(i_z) = \left[ \frac{Z_{\text{obj}}(i_z) - Z_{\text{obj}}(0)}{Z_{\text{screen}}} \right] \cdot \Delta X_{\text{view}} \quad \text{if} \]  

(22)

\[ \Delta X_{\text{objjump}}(i_z) < \Delta X_{\text{obj}}(z) \]

then no jump takes place. In the other cases the jump is quantized by \( \Delta X_{\text{obj}}(i_z) \).

### 6.5 The dynamic object resolution

In some cases stroboscopic effects can happen when an observer is moving his vertical position. The jumping effect, of course, can be avoided by low pass filtering which reduces the resolution. The limit for this will be called dynamic resolution. This new kind of dynamic resolution is only valid in the horizontal direction. According to the above equation it is given by

\[ \Delta X_{\text{objdyn}} = \text{Max} \left\{ \Delta X_{\text{view}}, \left( \frac{Z_{\text{obj}}(i_z)}{Z_{\text{screen}}} - 1 \right), \Delta X_{\text{obj}}(i_z) \right\} \]  

(23)

If an object to be shown is situated in the screen plane than the resolution is only limited by the pixel difference of the screen \( \Delta X_{\text{screen}} = L_S \cdot \text{pitch} \), given by the pitch of the lenticular structure.

### 6.6 Filtering Operations

Within each z-plane \( z=Z_0 \) an equidistant sampling is defined by the pixel difference of the screen: \( \Delta X_{\text{screen}}, \Delta Y_{\text{screen}} \) according to the fan projection for the static resolution:

According to this distances the local Nyquist frequencies for low pass filtering are given by

\[ f_{\text{NyX}} = 1/(2 \Delta X(z)) \quad \text{resp.} \quad f_{\text{NyY}} = 1/(2 \Delta Y(z)) \]

Then the

\[ \Delta Y_{\text{obj}}(z) = \Delta Y_{\text{screen}} \cdot \frac{z}{Z_{\text{screen}}} \quad \text{with} \quad Z_{\text{obj}} = 0 \]  

(25)

low pass filtering for the z-plane \( z=Z_0 \) can be done at the point \( x_0, y_0 \) by the functions

\[
\text{si}[\frac{(x - x_0)/(2 \Delta X)}{2\pi \cdot (x - x_0)/(2 \Delta X)}] = \sin[\frac{2\pi \cdot (y - y_0)/(2 \Delta Y)}{2\pi \cdot (y - y_0)/(2 \Delta Y)}]
\]  

(26)

\[
\text{si}[\frac{(y - y_0)/(2 \Delta Y)}{2\pi \cdot (y - y_0)/(2 \Delta Y)}] = \sin[\frac{2\pi \cdot (x - x_0)/(2 \Delta X)}{2\pi \cdot (x - x_0)/(2 \Delta X)}]
\]

Let be \( B_{i,j} \) the picture in z-plane \( Z_0 \) and \( \delta x \) resp. \( \delta y \) very small sampling distances. The x-y-filtering then is carried out for the point \( x_0, y_0 \) by the sum

\[
B_p(x_0, y_0, z_0) = \Theta_{i,j} \cdot B(i \cdot \delta x, ki \cdot \delta y, Z_0) \cdot \text{si}\left[\frac{i \cdot \delta x - x_0}{2 \cdot \Delta X_{\text{obj}}(Z_0)}\right] \cdot \text{si}\left[\frac{ki \cdot \delta y - y_0}{2 \cdot \Delta Y_{\text{obj}}(Z_0)}\right]
\]  

(27)
In case a dynamic resolution is wanted $\Delta X_{\text{obj}}(Z_0)$ has to be substituted by $\Delta X_{\text{obj} \text{dyn}}$.

The not equidistant $z$-Planes $Z_{\text{obj}}(iz_i)$ for sampling are given by equation (13). The filtering function for the $z$-coordinate at the point $z_0 = Z_{\text{obj}}(iz = i_0)$ is derived as follows:

$$f(z, z_0) = \sin\left[\frac{1 - Z_{\text{screen}}/z - i_0}{2\Delta D}\right]$$

with $\Delta D = \Delta X_{\text{screen}}/D_{\text{eye}}$ (28)

Thus the filtering sum for the smaller sampling distances $\delta z$ will be

$$B_f(x_0, y_0, z_0) = \Theta_{i_0} B_p(x_0, y_0, z_0) \cdot f(n \delta z, z_0)$$ (29)

according $Z_{\text{min}} < n \delta z < Z_{\text{max}}$

This completes the description of the three dimensional filtering operations.

Normally the object image datas are given also sampled. Then the analogue function or resampling function is achieved by the known sum using $\sin$-functions.

7. Adaptivity

Of course, it is not easy to believe that such a high precision in the range of some micrometers can be achieved by laser beams, changes of temperature can cause already such displacements. The only way is a electronical continous feed back adaption being integrated in a special control chip which can run with a high frequency of 200 MHz or more. That does not mean that the feed back has to react within such a small cycle; a delayed measurement signal can be used, too, because it is repeated contiiously.

The modulation of the laser beam is based on an adaptive loop, which controls exactly the correspondence between time and local coordinates on the display. Thereby, the local writing reaches the sufficient precision which in addition compensates thermal frame buckling.

Using a written high resolution black-white transparency instead of the LC layer, it is possible to demonstrate the 3D-image quality without specially designed laser units. Such a first model has been presented at the IPM at Kassel university. Therefore, a hologram display will be briefly called a "Kassel Display".

8. Main Components

Fig.7: Coordinate system, with viewing planes and representation planes

The main functional layers of the 3D color display are shown in fig. 7. When the liquid crystal panel (10) is substituted by a black/white photo film, the arrangement is called 3D Photo Display. The adjustment of the precisely mounted film is done mechanically by very small cones and holes.

The main components are summarized as fol-
- Lenticular glasses carrying color and brightness masks on the back side,
- binary written (black/white) \( \ell \)-pixels on a display or photo film,
- electronically erasable and writable by available and non-dangerous infrared lasers on liquid crystal scattering display (LCSD), writing period for one pixel: approximately \( 1 \ \text{s} \),
- electronic control consisting of specially integrated CMOS-chip devices,
- alternatively mounted and micromechanically adjustable photo film carrying the coded 3D data.

The main advantageous features of the 3D color display are listed up in the following:
- Limited real time performance on chosen areas on the display - e.g. to watch minimal-invasive surgeries,
- integration of densely packed displays to a large 3D picture for architecture or advertising,
- for the first time full 3D color imaging,
- simultaneous 3D vision for a group of observers without any additional aid,
- pure digital binary technology down to the photo mask or scattering display, hence analogue disturbances cannot occur anymore,
- affordable 3D application in the field of practical medicine by using a central radiology station and portable cheap photo-mask carrying directly visible 3D images through the suitable illuminated lenticular screen,
- once a 3D picture has been written on a LCSD, it can store the information for years without consuming energy,
- no disturbing discrepancy between level of focus and level of parallax for the human eye since more than 100 viewing directions are produced; whereas in conventional pure stereoscopic systems using two views, this discrepancy cannot be avoided, cf. shutter or polarization glasses in "3D cinemas" can cause a headache when used over a longer period,
- option to future development and extension: option to increase realtime performance because of short writing time per pixel in \( \ell \)'s range, and the possibility of laser array design.

9. 3D Photo Display

Fig. 8: 3D color photo display offering 100 different views on a 18 inch TFT display

A model of a 3D color display has been realized by a display having substituted the liquid crystal layer by a photo film. The functions of the color and the brightness masks can be substituted by a standard TFT screen. Fig. 8 shows a photo of such an arrangement in which a 18 inch TFT screen is used to demonstrate the quality
achieved of the 3D images. The difference to a true 3D photo display: colors appear in dependence from the vertical observer position. Therefore, a predefined vertical eye position range is necessary to get the true colors. Such an arrangement has been developed for medical applications to show computer tomograms from MR (magnetic resonance) data in which the color is freely chosen. This display now has got a resolution of 570 x 640 x 100 (WxHxD) 3D pixels with full color quality. The 3D coded black / white film has got a resolution of 5080 dpi.

10. Applications

Main applications are foreseen in the medical NMR- (Nuclear Magnetic Resonance) and X-ray tomography. Architects can use these laser-written 3D-displays with even more advantage when several display glasses are put together to form a huge 3D-poster of a computer-designed building. Designers and artists being familiar with computer aid will find a direct 3D vision support.

11. Future Development

Real time features would be very attractive, but they are not available yet. This binary LC-display allows to develop a mixed version of still not moving image environment and a limited real time moving region which can be addressed variably. The real time performance can be increased enormously when independently codable laser arrays will be used. This will be specified by a future R&D project. Of course, modifications of ultra high resolution 2D-displays can be derived.

12. Conclusions

- For the first time the concept of a high resolution 3D color display has been presented.
- The self adjusting adaptive laser writing and the modular principle will allow large screen size extensions.
- A photo display model of size 20 inch x 14 inch was presented at the ICCE showing up to 100 views (or depth pixels)
- A TFT based 18" monitor 3D photo display for medical applications has been shown at the ICCE exhibition room.
- Largest size of a photo display available (for the time being): 32 x 20 inch² carrying 1600 x 1024 x 100 3D color pixels.

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References


