https://doi.org/10.2352/ISSN.2470-1173.2017.5.SD&A-377

A new design and image processing algorithm for lenticular lens displays

René de la Barré, Roland Bartmann, Mathias Kuhlmey, Bernd Duckstein, Silvio Jurk, Sylvain Renault
Vision & Imaging Technologies
Fraunhofer Heinrich-Hertz-Institute, Berlin, Germany

Abstract
In this study, a new autostereoscopic 3D display design approach based on our patent specification is proposed and demonstrated. In contrast to common autostereoscopic two-view-designs with lenticulars, our approach allows more distance between image splitter and display panel. In comparison to 3D displays showing details at nominal distance, our design projects the images to a near zone in front of the display. As a consequence, the low magnification factor reduces distance errors from relative movements of display panel and image splitter. An image processing algorithm was developed to arrange the content and correct display shortcomings of image allocation caused by optical properties of the lenticulars. In addition, this algorithm allows static adjustment and tracking of observer position in a defined area in front of the display. We integrated the display in a production chain for digitalization and presentation of cultural heritage objects and developed special web-based modules for stereo rendering and user interaction, so that observers may explore cultural content in a natural manner.

Introduction
Today, new desktop and tablet displays show a highly increased resolution. This is an advantage for the design of autostereoscopic displays (ASD). ASD need several interleaved images and with such a high overall resolution it is possible to reproduce a good single view resolution, as well. Due to smaller subpixel structures, the image splitter needs a reduced lens pitch as well as increased accuracy when aligning with the LC-panel. By getting the image splitter as close as possible to the display structure, some properties of image separation are unfavorable. The influence of distance flaws will be increased. The smaller distances affect the lenticular pitch and thereby optic aberrations like the Petzval field curvature [1, 2]. Due to the latter, the quality of the stereo image deteriorates with a wider observing angle. A design approach to reduce angle dependence and panel waviness is an increase of lenticular lens radius. This is familiar from the patent literature [3]. The concept is based on a smaller magnification factor of the proposed 3D system. Thereby the stereo image is composed by several different image strips.

Also quite important for perception of good 3D images is the delivered depth. Our novel 3D display can show more depth than conventional flat autostereoscopic designs with smaller lenticulars. The presented depth of an autostereoscopic panel is proportional to the lens pitch [4]. Therefore, the proposed design is equipped with an image splitter with comparatively large lens pitch in the millimeter range. That concept of lower magnification was already used for ASD design [5]. It is significant different to the traditional design approaches known from literature [6].

We implemented the idea of aerial-image representation. The intermediate image in the so called air-image plan can be made visible by a physical plane for instance a simple sheet of paper. To get such kind of image, the matrix pixel plane has to be located somewhere between simple and double focal point distance of the lenticular. The 3D model, image algorithms, optic simulations and experimental validation of the novel two-view ASD design will be presented.

To bring out the quality of the 3D display, we integrated it in a content production chain for cultural heritage objects combining different scanning techniques, computer graphic methods and 3D web rendering tools. Such models are mostly complex and should be visualized with a lifelike level of details. Additionally, we developed a web compatible display driver and appropriate interaction modules in *JavaScript* and HTML for the Fraunhofer IGD renderer *x3dom*, a web-based library allowing a seamless integration of 3D content into a webpage [7].

Display model and simulation
Conventional ASD are often multi-layered flat panel designs. Our novel air-image setup is also based on the lenticular image splitter type.

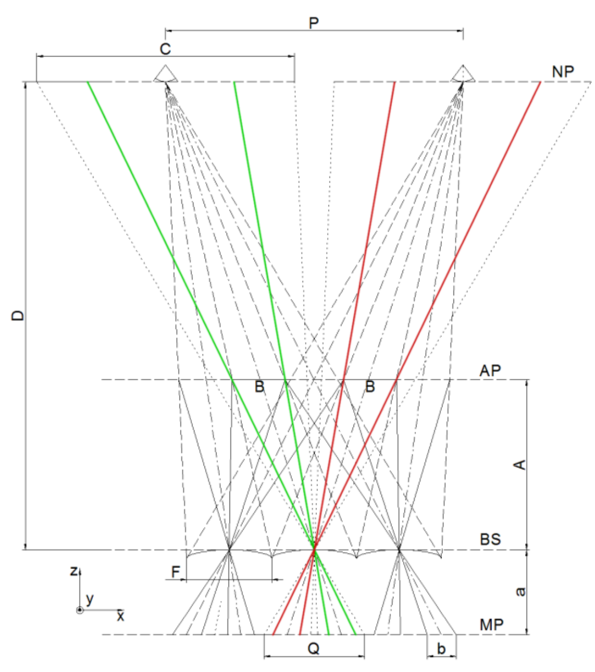

Figure 1. *Top view scheme of the air-image display with red for left and green for right content, light ray distribution from an exemplary part of matrix pixel panel MP through the image splitter BS to the eyes position (at the middle of projection width C in distance P) in nominal plane NP; b is a single image strip in MP and B the projection in the air plane AP; A, a and D are different distances between AP, BS, MP and NP.*

The lens grid separates the stereo strips in the pixel plane of the display. In contrast, lenticular parameters and distances are different from the majority of common designs and the underlying principle is described in detail in former literature [3].

The geometric conception of the proposed 3D display is depicted in Figure 1. Different light paths of an exemplarily chosen stereo image section are shown. In detail, several subpixels of the matrix panel *MP* are emitting light rays of displayed image content to the eyes of observer. All image strips *b* will be projected as optical air-image in *AP* through a vertical aligned cylindrical lens array *BS*. The projected air-image consists of different *B* sections.

However, optical imaging of real objects is applicable for cylindrical lenses only at the perpendicular profile of cylinder axis [1]. The human eye is able to dim the resulting image intensity and therefore able to separate a single view direction-dependent. The eye pupil of the observer in nominal plane *NP* selects images in viewing direction out of a variety of stacked projected images in *AP* and provides a comparable sharp image perception. In this schematic model, stereo sections are calculated based on the geometrical stripe width and distance parameters. For the eye, only image areas are visible inside connection line between the eye pupil periphery and the edge regions of the cylindrical lenses. These sections *B* in the geometric scheme in Figure 1 are projections of left and right image content of strips b_r and b_l. All sections of width *B* from one single view will be combined to a continuos 2D image in *AP*. Afterwards, the different views will be separated again in the stereo zones at nominal distance *D*.

For a first evaluation of the proposed model we used our in-house simulation tool [8]. The two-view system was calculated by a implemented Monte Carlo approach.

Table 1: 3D display simulation parameters

Parameter	Description	Value	Unit
P	IPD	65	mm
D	nominal distance	1,2	m
a	display to lens distance	69,5	mm
L	lens pitch	5,90909	mm
Q	image strip width in MP	6.25485	mm

The main parameters used for this calculation are listed in Tab. 1. As a result stereo viewing zones of 2 x 52 mm width were detected in 1.2 m distance. The result is shown in Figure 2. Red and green color represent both views for left and right eye position.

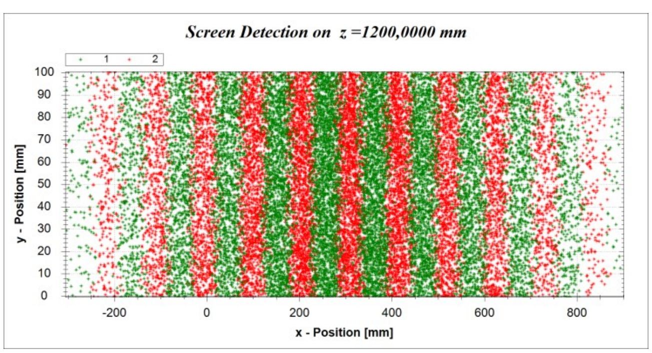

Figure 2. *Screen detection plane in 1.2 meter distance to the 3D display, two views separated by green and red color, every single Point represents one emitted ray from the pixel plane, display width of around 0.6 m, x/y-position zero is the lower left corner of the display.*

In addition to the view separation, the investigation of luminance distribution in *NP* was simulated too. In Figure 3 the integrated intensities of the two views are depicted. According to the simulation results a good stereo separation of the viewing zones in NP is expected. After the first proof of view separation in the proposed lenticular lens display the image generation by an adapted allocation algorithm was implemented and tested in the following chapters.

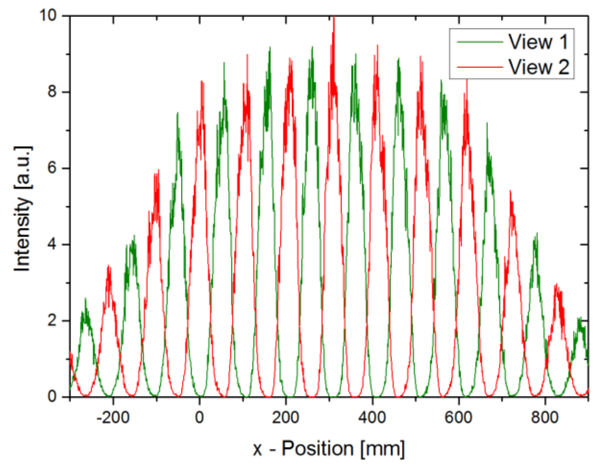

Figure 3. *Integrated light intensity of the views in 1.2 meter distance to the 3D display, two views separated by green and red color, display width of around 0.6 m, x-position zero is the left edge of the display.*

Image generation

The image allocation used for image stripe arrangement will be explained in detail, see Figure 4. These sections are described as b_l and b_r and will be reproduced, laterally reversed on stereo image layer *AP*. Therefore, the observer only sees a partial section of width *b*. Inside range *c* it is possible to locate *N* pixels and therefrom in section *b* a subset of it. For the case that the observer distance to the display will be changed, the pixels in an image strip shift from visible areas to invisible areas and vice versa. Meanwhile the observer is still looking at an undisturbed image. Because the width of reserve sections g_i is dependent on the change of distance to the panel.

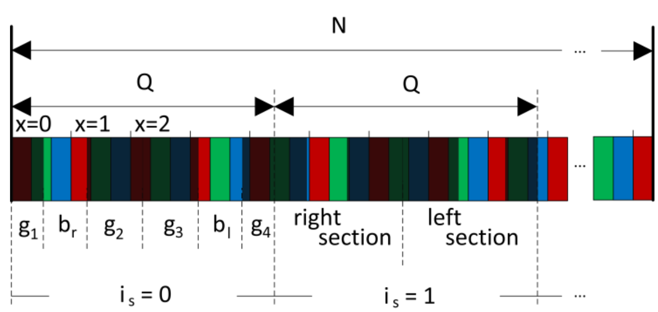

Figure 4. *Schematic, representation of a horizontal subpixel row segment in MP (front view), image stripes b_i and reserve sections g_i, uniform block width Q and resolution N.*

The arrangement requires a new interleaving pattern and the use of a standard side-by-side stereo image format. This image format has to be converted internally in horizontal anamorph images with a side ratio of approximately 1:3. In our experimental setup, see further details in the last chapter, we used a magnification ratio of 1:2.4. The image has to be divided in stripes that partially overlap. Therefore, redundant information will be inscribed in the peripheral image stripe areas. The position of the stripes inside the partial image can be changed dynamically by controlling the interleaving parameters through a tracking signal. This will enable stereo image adaptation to the tracked observer position.

Image algorithm

In mathematical terms, the algorithm implements a transformation of pixel coordinates from an initial image with horizontal resolution N_0 to converted pixel coordinates of the used image for the 3D display. The edge point of the display is the zero point for the x-coordinate, angle α describes the viewing angle. A source image with a given horizontal resolution N_0 will be converted to pixel coordinates $x'_{r,l}(x,\alpha)$ of an image composed by image strips that are merged together in a different order, see equation (1). The resolution of right and left image has to be the same. Otherwise we have to scale it to the same resolution.

$$x'_{r,l}(x,\alpha) = \frac{N_0}{N} \cdot \left[x + x_s + \left(h(x) \pm \frac{s+d}{2}\right) \cdot \frac{F \cdot Q}{b(\alpha)}\right] \quad (1)$$

This equation is the mathematical representation of that coordinate transformation where *x'* is the x-coordinate of the source image for left or right image. The value N_0/N describes a resolution ratio. Furthermore, x_s is a shift value that represents the slope of the grid and also includes the observer position dependent on a tracking value. This value influences the x-position of the image. A tracking of the observer distance will be realized by changing the parameter *Q*. The value *h(x)* as block position in equation (2) describes a coordinate mapping within one block. If *x* is at the right section of content information then $Q_0 = 0$ and if *x* is at the left section then $Q_0 = Q/2$.

$$h(x) = Q_0 - frac\left(\frac{x+x_s}{Q}\right) \cdot Q \quad (2)$$

In addition to equation (1), the disparity value *d* results from position change of image left against image right. *F* and *b(α)* describe the required scaling factors to corresponding pixel positions of the original image. The scaling compensation factor *F* corrects the offset error. Function *b(α)* is angle dependent and results from a correction of strip enlargement by an increased observation angle *α* that will be described in detail in the following chapter.

Error correction by light ray simulation

The image processing algorithm was tested and validated by optical modeling software and in the experiment; the used parameters, with pixel pitch p, are listed in Table 1.

The width of the image stripes in *MP* is angle dependent. Hence the observer in viewing distance *D* perceives different image stripe widths from respective viewing directions. For the experimental setup from Table 1 the viewing angle is in the range from 0 to 14°. The stripe width will be increased due to wider viewing angle and more distance to the focal point of a single lens element. The reasons for that are aberration effects or simplified the Petzval field curvature due to inclined incidence of light [8].

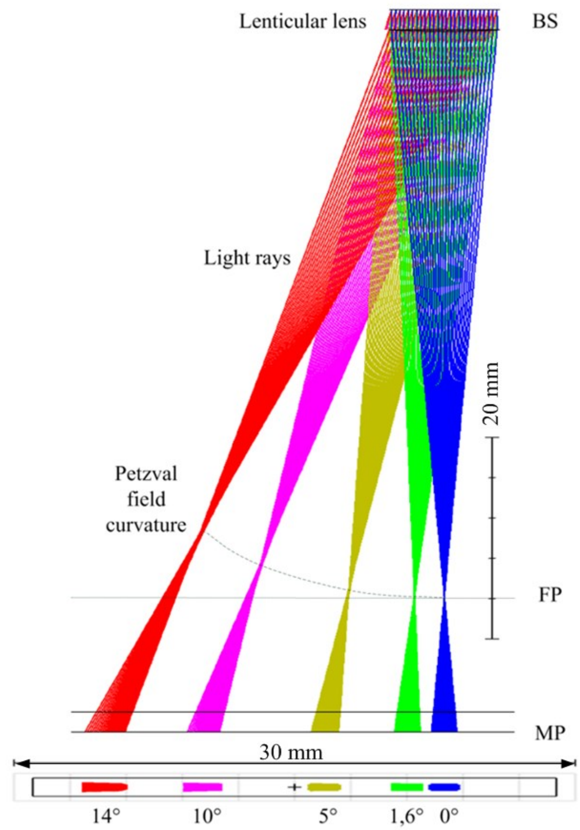

Figure 5. *Exemplarily chosen single lens for simulation of angle dependent light ray distribution between BS and MP, Focal plane FP and Petzval field curvature are depicted, viewing image stripe width is proportional to viewing angle.*

Figure 5. shows the angle dependent stripe width by using the optical simulation software Opticstudio™. For specific arrangements or 3D display setups the relation between angle and strip width has to be investigated in detail. The parabolic dependence of stripe width from viewing angle and wavelength is depicted in Figure 6.

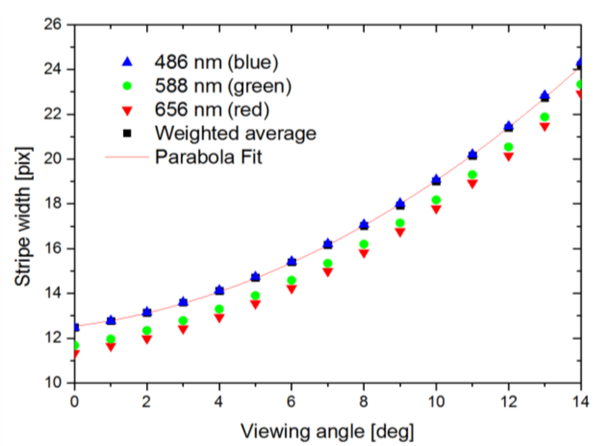

Figure 6. *Adaptation of Petzval field curvature, wavelength and angle dependent strip width in pixels was derived from optical simulation data and fitted by a parabola curve.*

The results were determined by optical simulations and the weighted average data was mathematically fitted by a parabola. Function b(α) in equation (3) describes that angle dependency, where c0, c1 and c2 represent the constants of regression.

$$b(\alpha) = c_2 \cdot \alpha^2 + c_1 \cdot \alpha + c_0 \tag{3}$$

The parameters for average adaptation of the Petzval field curvature were c0 = 12.5, c1 = 0.206 and c2 = 0.045. The angle α respects the viewing position in front of the display. Therefore, the correction is realizable for tracking as well. The position of the observer can be transformed into this angle. The depicted adaption in Figure 6 limits the possible viewing space by its range and the feasible maximum stripe width. The application of the proposed strip width adaptation is shown in the image presentation in the next chapter.

Experiment, Results and application

An autostereoscopic air-image 3D display was developed and examined by using a 5K panel with a large-sized lenticular lens grid.

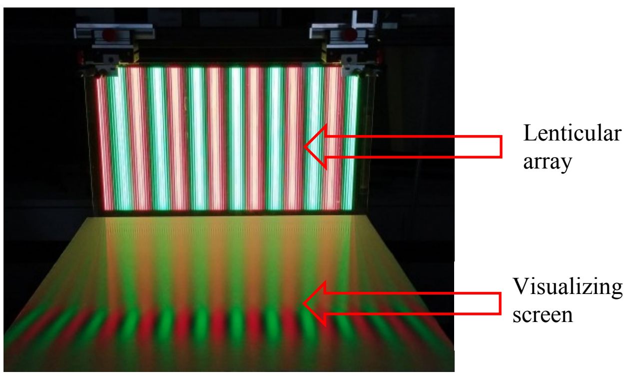

Figure 7. *3D display setup with test content.*

In common autostereoscopic lenticular lenses displays the dimmed stereo image by eye aperture is directly composed on the image splitter plane *BS*. In contrast, the proposed novel 3D display depicts a real air-image in front of the lenses array at *AP* composed of stereo image stripes.

The 27” 3D display mock-up was realized on a test carrier with micro meter drives for distance adjustments. In Figure 7 the display setup consisting of a vertical lenticular array and a matrix panel in landscape format is depicted. An additional reflecting screen for visualizing of light ray paths was attached too. The used display was a DELL UP2715K with a pixel pitch of 0.11655mm and a resolution of 5120xRGBx2880 pixel. The lenses raster plate was produced in resign on glass technology with 2 mm carrier glass and with a lens radius of 26.9mm. For the display control a Windows 8 PC (ASUS ROG G20AJ-DE045S) with an NVidia 980 GTX graphics card was applied. A GPU based software render tool developed by Fraunhofer HHI was used for image processing and content multiplexing. The algorithm used the acceleration of DirectX11 libraries to generate the displayed pattern.

For the documentation of results a CANON EOS-1 Ds Mark II camera and contrast enhancement software were used. To prove the projection of the air-image a RGB-test image with three respectively different colored image stripes was created.

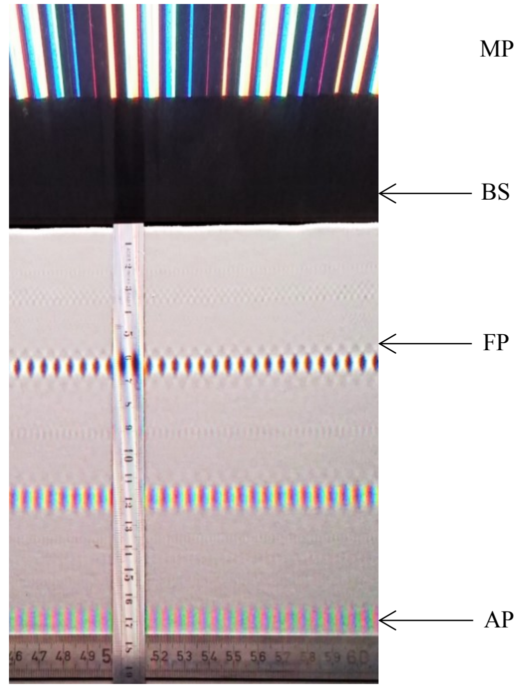

Figure 8. *Horizontal light distribution with alternating colored strips in several distances to image splitter BS and pixel plane MP, anterior focal plane FP is barely visible; RGB-pattern is sharply separated in 17 cm distance from BS at air-image plane AP.*

All image sections b_r and b_l were filled with one equally distributed RGB-stripe. The emerging ray picture was visualized on a white screen, shown in Figure 8. In different distances to *BS,* several centimeters away from focal plane *FP,* the color distribution is changing. The best color separation was provided by the real air-image in 17 cm distance at air-image plane *AP*. The perceived RGB-image is merged correctly in that distance only. The RGB-stripe pattern presents either the left or right view of the stereo image. It was demonstrated that periodical superimpositions with alternate changing colors exist in the projected light field.

Figure 9. *Mock-up of the 3D display showing content from Fraunhofer cultural heritage project. The view is assembled from the overlapping image stripes.*

To operate and test the new 3D display, we implemented new rendering modules and used scanned objects created by the Fraunhofer cultural heritage project. The main objective of this current project is to create a processing chain for the digitalization and the presentation of cultural objects as sculptures, statues and parts of historical monuments, into consideration on their different materials (sandstone, marble, wood etc.). These objects are very suitable to bring up the stereo capabilities and quality of the display because they have complex forms and contain important details that have to be presented in a lifelike manner. In general, digitalization can be done by scan sensors (new methods are developed and tested in the project) as well as by 3D reconstruction algorithms for static objects and dynamic bodies [9].

Figure 9 shows first results of scanned objects viewed on the new display and rendered in real-time inside an interactive webpage, here in full screen mode (from left to right: „Kreuzblume“ by Fraunhofer IPM and Münster Freiburg; „Terracotta Krieger“ and „Dave“ by Fraunhofer IGD). To render the scene in stereo and process user interaction as body gesture, we created some *JavaScript* and *HTML* extensions in the *x3dom* library.

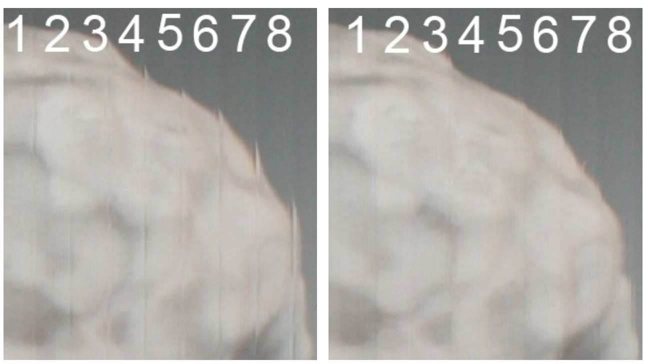

Figure 10. *Magnified image section of Figure 8, on the left side without and on the right side with applied correction algorithm for image stripes (1-8).*

Special display drivers and tracking modules for head and hand tracking were implemented and tested. Interactive web-based 3D scenes for suchlike auto-stereo displays can be done in an efficient way. The content shown in Figure 10 was rendered via the extended library and processed by image allocation and correction algorithms described in the first chapters. The two pictures demonstrate the differences in the image strip alignments. In table 2, N_0 describes the resolution of the source image shown in Figure 9 where N is the resolution of the pixel panel.

Table 2: Constant input parameters of the proposed image processing algorithm equation (1) for Figure 9 and 10.

N_0	N	Q	s	x_s	d	Q_0	F
1920	5120	53,67	9	0	0	0	1,17
pixel	pixel	Pixel	pixel	pixel	pixel	pixel	

The values Q and s depend on the viewing distance and system parameters of the 3D display. Due to the chosen setup the slope angle of the grid is zero. The central camera position is fixed in front of the panel, therefore x_s is constant zero. In addition, the disparity value d is zero because there is no shift between the images. The parameter Q_0 is zero due to the block position for the right views. F as compensation factor results from calibration to improve the image quality.

Table 3: Parameter comparison of variable values in pixels by stripe numbers shown in Figure 10

No.	1	2	3	4	5	6	7	8
x	4373	4427	4480	4534	4588	4641	4695	4749
α	10,0	10,3	10,6	10,9	11,1	11,4	11,7	12,0
h(x)	0,8	0,5	1,2	0,8	0,5	1,2	0,8	0,5
b(α)	19,1	19,4	19,7	20,0	20,4	20,7	21,1	21,5
$x_r'(x, \alpha)$	1646	1666	1687	1707	1726	1747	1767	1786
$x_r'(x, 0)$	1650	1670	1691	1710	1730	1751	1771	1790

The results shown in Tab. 3 exemplarily demonstrate the enlargement of the visible image stripes 1 to 8. In detail the angle dependent correction of $b(\alpha)$, see Figure 6, and $x_r'(x,\alpha)$ was used. However, the selected area in the image is almost linear and the difference to $x_r'(x,0)$ is about four pixels.

Summary

For this considered single user approach, with a magnification of 2.4:1, a plurality of pixels will be covered by one lens for each row. Several content-dependent subpixels are joined together to constitute an image stripe either related to the left or right observer eye. Invisible from the current observer position, adjacent subpixels ensure reserve zones and allow a wider viewing space. Light rays from the intermediate image in the projection plane were selected by eye aperture. Thus, the observer will perceive a 3D stereo image with good quality and depth.

Compared with conventional 3D display designs of 100-times magnification and column multiplexing, it is a lot easier to adjust display matrix and lens grid. The influence of display waviness and distance errors of lens grid and panel are minimized. For the experiment a non-corrected lens grid with wide cylindrical lenses was used. It could be proven that the used image processing algorithm allows the dynamic correction of the arrangement and optical errors.

The perceptible displayed resolution is defined by the distance-dependent magnification. Compared to the observing position a tracking is necessary for representation of image content with no delay.

Then, the stereo image will be continuously adjusted by the position of the user’s head. The scene will be explored from different perspectives while the observer moves laterally in front of the display. Furthermore, the user will be able to interact with the virtual content via gesture in a natural manner (e.g. for rotation, selection, etc.) because virtual objects float in the air, close to him.

Conclusion

A new approach for designing two-view ASD was presented. The effects of this design were discussed. Therefore an optical ray tracing model and various image processing algorithms were developed and tested by simulation and experiment. It was proven that a real 3D image with high quality and low magnification is feasible. The low image magnification reduces the influence of misalignment errors between display screen and lenses raster on the viewing quality. Then the enhanced distance is large compared to the waviness of the display panel.

The substrate layer for the lenses creates only low intra ocular crosstalk effects. Furthermore the perceptible 3D depth is increased, compared with common 3D displays.

The integration of the display and software modules in a production chain for digitization and presentation of museum and cultural objects demonstrates well the feasibility of the techniques. Now, with this web-based solution (*x3dom* renderer and extensions) 3D content can be presented on such stereo displays over the internet, lifelike, with a high fidelity and depth. Thus, the floating object close to a museum visitor tempts him to interact with it. Of course, the interactive stereo display can also be used for other scenarios e.g. for automotive, construction and medical applications as well as for gaming or entertainment.

Acknowledgement

We would like to thank the Münster Freiburg as well as the Fraunhofer IPM and IGD for the provided image content. Financial support by Fraunhofer-Gesellschaft, Munich (grant no. 600296) is gratefully acknowledged.

References

[1] H. Haferkorn. Optik: Physikalisch-technische Grundlagen und Anwendungen, Kap. 4, Leipzig; Berlin; Heidelberg: Barth Verlagsgesellschaft mbH, 1994.

[2] R. Kingslake. A History of the Photographic Lens, Academic Press Limited, Chap. 1, 273 p., 1989.

[3] R. de la Barré, S. Pastoor, and H. Röder. Autostereoscopic image display appliance for producing a floating real stereo image, *European Patent EP 2122415 B1*.

[4] I. Okoshi. Three-Dimensional Imaging Techniques, Academic Press Inc., 395 p., 1976.

[5] C. Großmann. Method and device for autostereoscopy, *European Patent EP 1090510 B1*, 2001.

[6] F. Dufaux, B. Pesquet-Popescu, M. Cagnazzo (eds.): Emerging Technologies for 3D Video, pp. 321-371, Wiley, 2013.

[7] X3dom-software, www.x3dom.org, Sept.2016.

[8] M. Kuhlmey, and R. Bartmann. Subpixel Area Based Simulation For Autostereoscopic Displays With Lenticular Arrays. *In Proceedings of the International Conference on 3D Imaging 2015 (IC3D)*, IEEE, 2015.

[9] W. Waizenegger, I. Feldmann, and O. Schreer. Real-time 3D body reconstruction for immersive TV. *Int. Conf. on Image Processing*, Phoenix, AZ, USA, Sept. 2016.

Authors Biographies

René de la Barré received his diploma in 1978 and his PhD in 1993 from the University of Mittweida. He worked for 20 years in R&D of display industries. In 2001 he joined the Heinrich Hertz Institute. Since 2003 he led the 3D display research there. In 2015 he changed to HHI's Capture and Display Group. His current research interests are design and human engineering of autostereoscopic 3D displays. He works in DIN, ISO and ICDM on autostereoscopic display topics.

Roland Bartmann received his diploma degree in 2002, in the physics department of the Humboldt University Berlin, and his Ph.D. degree from the Technical University Berlin, in 2009. After working in the area of neutron and x-ray optics, he changed to the display research at Fraunhofer Heinrich-Hertz-Institute in 2012. His research interests include physical and liquid crystal optics and the simulation of autostereoscopic 3D displays.

Mathias Kuhlmey studied computer engineering at TU Berlin (2014) and work for Heinrich-Hertz-Institute since 2011 as a research assistant. He developed a simulation environment for autostereoscopic displays besides mathematical modeling.

Bernd Duckstein after receiving his degree as a graduate engineer in communications engineering at the University of Applied Sciences of the Bundespost in Berlin, Mr. Duckstein joined the Heinrich-Hertz-Institute in 1986 as research associate. Working in the 3D autostereoscopy group, he worked on many hardware, software, content and measurement issues of autostereoscopic display systems.

Silvio Jurk studied technical computer science at the University of Applied Science in Görlitz(2009) and computer science for media at HTW Berlin (2013). In 2008 he joined the Advanced Displays and Applications Group at Fraunhofer Heinrich-Hertz-Institute where he has been working on adaption procedures and display designs in the area of 3D displays. In 2015 he changed to the Capture and Display Group. His current research interests include autostereoscopic 3D displays and image based technologies.

Sylvain Renault received his diploma degree in Computer Science from the Technical University of Berlin,Germany, in 1997. He has been working for the Fraunhofer HHI in the Interactive Media and Human Factors department in the research field of computer graphics, virtual reality and novel human–machine interaction technologies. He developed the 3D real-time software framework Workbench^{3D} with numerouosly applications for it. In 2015 he changed to HHI's Immersive Media and Communication group.