SIGRAD 2014
M. Obaid, D. Sjölie and M. Fjeld (Editors)

Mirror Stereoscopic Display for Direct Volume Rendering

F. M. M. Marreiros[1,2] and Ö. Smedby[1,2,3]

[1]Center for Medical Image Science and Visualization (CMIV), Linköping University, Sweden
[2]Department of Science and Technology (ITN) - Media and Information Technology (MIT) , Linköping University, Sweden
[3]Department of Radiology (IMH), Linköping University, Sweden

Abstract

A new mirror stereoscopic display for Direct Volume Rendering (DVR) is presented. The stereoscopic display system is composed of one monitor and one acrylic first surface mirror. The mirror reflects one image for one of the eyes. The geometrical transformations to compute correctly the stereo pair is presented and is the core of this paper. System considerations such as mirror placement and implications are also discussed.
In contrast to other similar solutions, we do not use two monitors, but just one. Consequently one of the images needs to be skewed. Advantages of the system include absence of ghosting and of flickering.
We also developed the rendering engine for DVR of volumetric datasets mostly for medical imaging visualization. The skewing process in this case is integrated into the ray casting of DVR. Using geometrical transformations, we can compute precisely the directions of the rays, producing accurate stereo pairs.

Categories and Subject Descriptors (according to ACM CCS): I.3.1 [Computer Graphics]: Hardware Architecture—Three-dimensional displays

1. Introduction

Stereopsis or binocular disparity is one of the most important binocular depth cues for close range visualization (personal space or action space) [CV95]. Using two images (one for each eye) at slightly different angles, it is possible to triangulate the distance to an object. To do so, our brain has to find corresponding points in both images (stereo matching) and then triangulate. In some cases, regions might be occluded in one view; for these regions other depth cues come into play.

We have developed a stereoscopic system that is, in principle, similar to other stereoscopic systems, i.e., we need to generate the stereo pair and display each image to the correct eye. The difference between stereoscopic technologies lies in how the images are presented to the viewer.

Here we will only consider systems with relatively large screens like typical monitors. Thus we exclude head-mounted displays and similar systems that make use of small displays.

The most common active stereo display technique is shutter glasses, where the display is synchronized with the opening and closing of the shutters of the glasses, so that the viewer views just one image at a time [Nvi12], [Bar03]. The drawback is the synchronization process that might not work perfectly, producing ghost artefacts (crosstalk), and the risk of prolonged usage triggering epileptic seizures due to flickering. Other passive systems include:

- anaglyphs, that use glasses with colour filters to filter the images, limiting the usage of colour. Ghosting can occur as the colour filters are not perfect;
- polarized, where special screens are used to display images with different light polarizations and special glasses are required. They suffer from ghosting due to light polarization crosstalk;
- wavelength multiplex imaging [JF03], where light is separated into three spectral ranges and special glasses are used with filters for specific spectral ranges. It also suffers from ghosting due to spectral range overlapping.

There are also autostereoscopic displays from several brands in the market. Two examples of this are parallax barrier and lenticular autostereoscopic displays [Ber96], [Ive02]. In fact, the principles of this technology are rather old, but were made available by the new LCD screen technology. For a more complete survey of stereo display systems, see [Hol05], [KH07].

1.1. Related work

Dual monitor systems [KH07], [FRM*05] can also be used for stereoscopic viewing. The Planar StereoMirror 3D Monitor is an example that uses a semi-transparent polarized mirror [Pla]. Most similar to our system is a dual-monitor single-mirror system originally proposed by Hart [WC10], [Boh] where the viewer has to place his eyes at a certain angle between the edge of the mirror. The major benefit of this system is that there are no ghosting artefacts. Our system is based on the same concept, but a major difference is that we only use one monitor. To note that one single monitor stereoscopic system is also presented in: http://stereo.jpn.org/eng/stphmkr/mirror/mirrorview.htm. Although this system may seems equal to ours, in fact it is not because it does not compute the correct geometrical stereo pairs. Instead, it uses an approximation that can produce a reasonable stereo sensation because our visual system can compensate to a large extent positional errors.

1.2. Motivation

The motivation was to study alternative configurations to the dual monitor system (fixed configuration - same angles between components of the system) and still maintain its benefits. In particular we were interested in the possibility to simplify the system (by using only one monitor) and to understand the general implications of such new configurations on the system parameters in order to produce accurate stereo-pairs.

In the next sections, we will present the steps needed for the construction of the system and system considerations.

2. Stereo system design

The stereoscopic display system we have developed is composed of one monitor and one acrylic first surface mirror (First Surface Mirror, Toledo, Ohio, USA, http://www.firstsurfacemirror.com). This special mirror needs to be used because traditional mirrors have two reflections, one in the front layer and another in the back layer. If a conventional mirror is used, ghosting effects will be visible due to the double reflection. According to manufacturer specifications, the mirror has a reflectance level of 94-96%. This affects slightly the brightness of the colours, but fortunately the changes are small enough that our visual system can easily compensate for these variations.

As in most stereoscopic systems, two images are presented to the user in the same viewing window (display), one for each eye. For one of the eyes - in this case the left eye - this is trivial, but for the right eye, the aid of the mirror is required. Before placing the mirror, a choice must be made regarding the center of the viewing region and the viewing direction. In this system, the view direction is perpendicular to the view window and the center at the physical center

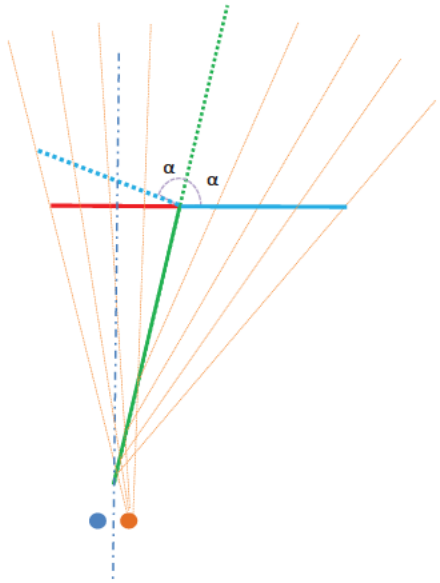

Figure 1: *Top view schematic presenting the left (orange) and right (blue) eye positions; the left (red), right (cyan) and reflected right (dashed cyan) viewing windows (the center of the left view window is presented in dotted-dashed blue); the reflected rays and their straight equivalent (dotted orange); the mirror position (green) and the angle of reflection.*

of the window. The configuration is different than in [Boh], where the view direction is angled. This configuration constrains the position of the mirror: The front edge (closer to display) is placed on the right edge of the view window and the back edge placed parallel to the vertical line at the center of the view window, Fig. 1 and 2. Note also the position of the eyes relative to the mirror: they have to be centered (around the back edge of the mirror) and at a small distance from it (80 mm). This small distance allows the face, in particular the nose, not to be in direct contact with the mirror, thus avoiding an uncomfortable position for the viewer. In this work, a fixed interpupillary distance of 65 mm was used. This value is slightly above the mean adult male of interpupillar distance 64.7 mm reported in [Dod04], [GCC*89].

The next step is to determine the directions of the reflected rays, using the law of specular reflection [Hea81]. The law states that the direction of incoming light (the incident ray), and the direction of outgoing light reflected (the reflected ray) make the same angle with respect to the surface normal and that the incident, normal, and reflected directions are coplanar.

To exemplify, we cast some rays from the right eye position and follow their path, as presented in Fig. 1. Here we can clearly see that we require an extra viewing window for

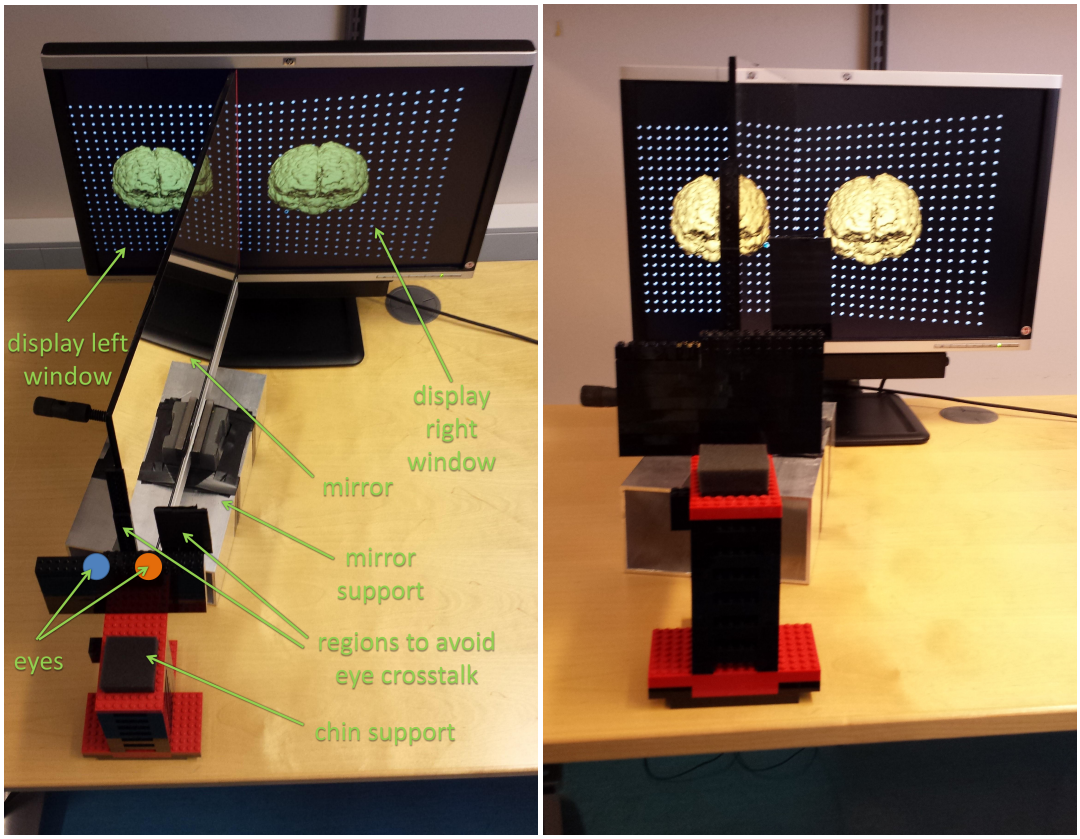

Figure 2: *Photographs of the stereo system prototype. On the left are included annotations of the system components and the eyes positions.*

the right eye. In practice, we have two viewing windows occupying two portions of the display (Fig. 2). The right window needs to have a larger length, due to the image skewing caused by the angle of the mirror. The reflection of the right viewing window produces a reflected window. To calculate it, the four vertices of the right window are reflected to obtain their 3D location. To do so, we use a reflection matrix introduced by Bimber et al. [BES00], [BFSE01]. If the mirror's plane is: $f(x,y,z) = ax+by+cz+d = 0$. The reflected points can be calculated by multiplying the reflection matrix with the original point: $\vec{p}' = M \cdot \vec{p}$.

$$M = \begin{bmatrix} 1-2a^2 & -2ab & -2ac & -2ad \\ -2ab & 1-2b^2 & -2bc & -2bd \\ -2ac & -2bc & 1-2c^2 & -2cd \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

Using the reflected right viewing window, we avoid calculating reflected rays (the equivalent straight rays are used) and construct two different scenes with the same virtual objects.

Once we know the position of both viewing windows (left and reflected right) and the eye positions, we can place objects in the scene and correctly render them. For the rendering, we use a ray-casting algorithm that casts rays from the eye position passing by the center of each individual pixel into the scene we want to render.

Before performing the rendering, the stereo region must be checked. For optimal results, the virtual objects should be confined to the stereo region. This region is defined by the intersection of the left and right view frustums (Fig. 3).

Regarding the viewing transformation, there is only one last transformation to perform: a horizontal image flip due to the mirror reflection. This inversion can be seen in Fig. 1 by looking at e.g. the leftmost ray that is not reflected which corresponds to the rightmost ray reflected.

3. System stereo pair rendering

This system was designed to render Direct Volume Rendering (DVR) [Lev88], [DCH88] stereo pairs. To generate DVR images, there are several possible algorithms. As mentioned previously, a DVR ray-casting algorithm was chosen because it follows precisely the geometry designed for our

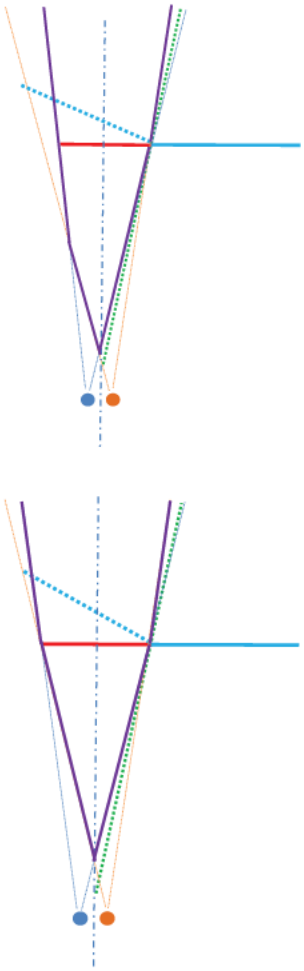

Figure 3: *Top view schematic presenting a non-symmetric (Top) and symmetric (Bottom) stereo region (inside the violet lines). The horizontal display size and mirror horizontal size are the same in both cases.*

system. Ray-casting works, as the name, indicates by casting rays from the observer position towards the scene. The direction of the ray is provided by the viewer position and the center of each pixel on the viewing window. The data used are regular grids with scalar values (voxels). These are typically acquired by medical image modalities such as Computed Tomography (CT) or Magnetic Resonance Imaging(MRI). The rays are sampled at fixed intervals and interpolated to obtain a scalar value (intensity). A transfer function relates intensity to opacity and color, thus calculating their contribution at each sample. Each ray, accumulates color and opacity along it until the opacity level reaches the maximum (opaque). In the case of surface rendering, the opacity for the voxels in the range of visible intensity values is always at the maximum, i.e. the rays will terminate when the object is first hit. Different illumination models and rendering styles can also be applied. Once the ray is terminated, the color values of the pixels that belong to the each ray are saved to produce the final images.

Illustrations of the casted rays for the right eye are presented in Fig. 1. The rays pass by the center of the pixels of the virtual window (reflected window). To obtain these pixel locations, the 3D positions of the edges of the virtual window are computed with the reflection matrix and the pixel positions sampled along this window. As previously mentioned, an image flip is then performed to render the image appropriately in the right region of the display.

4. System considerations

The construction of the system imposes certain limitations on the viewing angles. We limit these angles by introducing rectangular regions in front of both eyes through which the user will look. This is introduced for two reasons: first, we want to avoid crosstalk, since the eyes are placed at a small distance from the mirror, and second, with the right eye we only want to see the reflected image and not the image presented in the display.

According to [Hen93], the human horizontal field of view is approximately 200 degrees, but the stereo region is approximately 120 degrees. We should point out that the effective stereo region can be smaller, since the nasal angle is smaller than the temporal angle, i.e. some rays are obscured by the nose region.

In our case, this is not a problem, as we limit the field of views to the viewing windows, i.e. the rectangular regions limiting the field of view only need to allow the passage of the rays that pass by the center of each pixel (both viewing windows).

The stereo regions using the design presented in the previous section might be non-symmetric as presented in Fig. 3. To enforce the symmetry of the stereo region, constraints must be introduced. For the stereo region to be symmetric, the left-most ray of the right eye must cross simultaneously the left edges of the left and reflected right viewing windows. For fixed mirror size, display size, interpupillary distance and nose-to-mirror distance, the only parameter that can be optimized is the left viewing window size (by consequence the position and size of the other windows are also changed). The possible values of the left viewing window size are in the interval from 0 to half the horizontal size of the display. In order to sample pixel-by-pixel, the horizontal resolution must be provided. To solve this problem, a Matlab script was developed (available upon request) that computes the optimal horizontal size of the left viewing window. This value is obtained when the distance from the left edge of the reflected window to the left-most ray of the right eye (that passes by the left edge of the left window) is minimized.

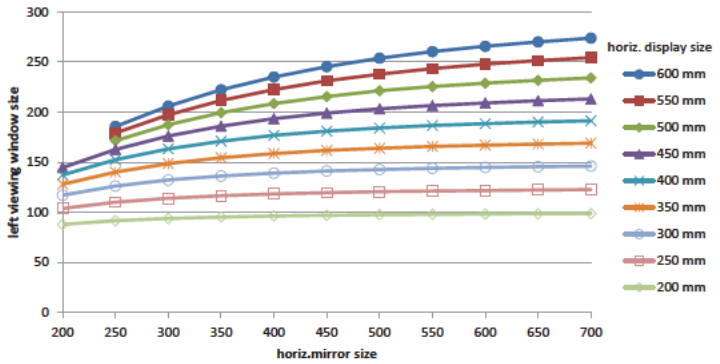

Figure 4: *Left viewing window size values by changing the mirror horizontal size and the horizontal display size.*

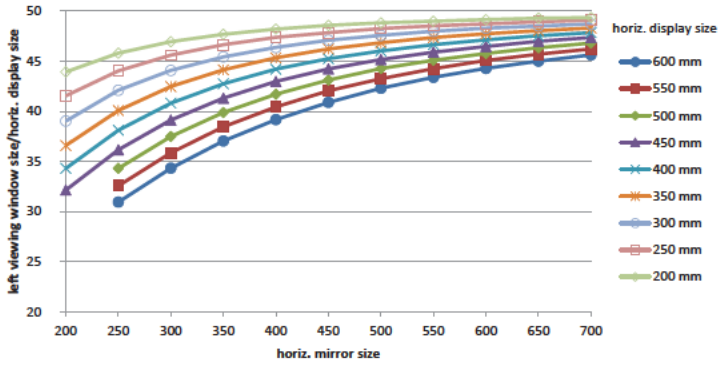

Figure 5: *Ratios of left viewing window size to horizontal display size by changing the mirror horizontal size and the horizontal display size.*

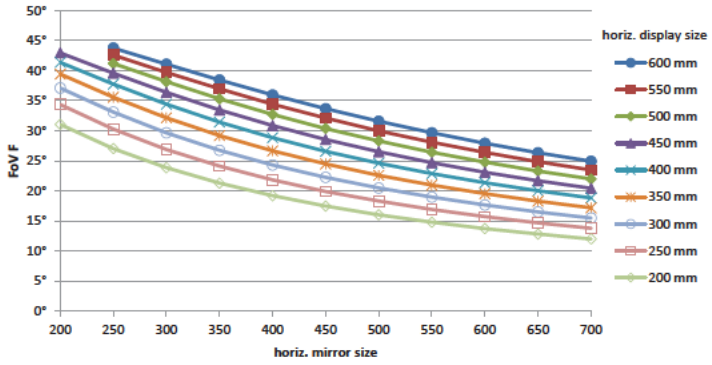

Figure 6: *FoV F (Field of View of the region in front of the viewing window) values by changing the mirror horizontal size and the horizontal display size.*

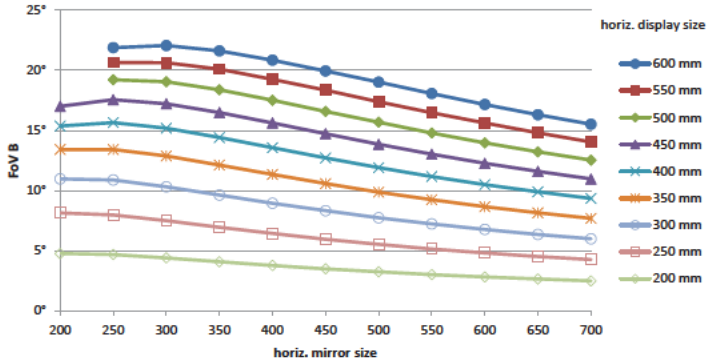

Figure 7: *FoV B (Field of View of the region behind the viewing window) values by changing the mirror horizontal size and the horizontal display size.*

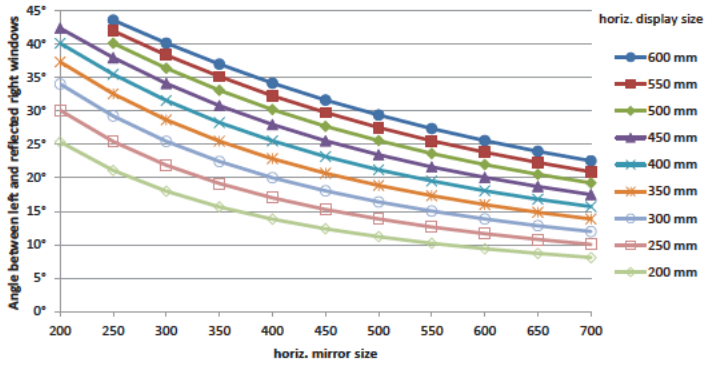

Figure 8: *Angles between left and reflected right viewing windows by changing the mirror horizontal size and the horizontal display size.*

To further study the system (with symmetry correction), the mirror size and display size were changed to explore how these affect the remaining system parameters. The results are presented in the graphs and examined in the next section. For the range of values studied, there are configurations that are considered invalid. These are the ones where the left-most ray of the right eye does not intercept the mirror or the right-most ray of the left eye also does not intercept the mirror. In the graphs these cases will make some lines start at higher values.

5. Results

The results show that the horizontal left viewing window size increases with the horizontal display and mirror horizontal sizes (Fig. 4). The ratio of the horizontal left viewing window size to horizontal display size is presented in Fig. 5. It shows that for smaller displays, the ratio is higher i.e. a more effective usage of the display is achieved. For larger mirrors, the horizontal left viewing area will approximate half the horizontal display size. In Fig. 6 and Fig. 7 are presented the angles of the two horizontal Fields of View (FoV) of the system (in front - FoV F and behind - FoV B the viewing window, as presented for the symmetric case in Fig. 3). For FoV F, the angles increase with horizontal display size and decrease with horizontal mirror size. For FoV B, the relation is more complex: the angles increase with horizontal display size, but there seems to be a maximum of the horizontal mirror size per horizontal display size. Finally, the angles between the horizontal left and reflected right windows increase with horizontal display size and decrease with horizontal mirror size (Fig. 8).

6. Discussion

The results show that most parameters are optimized by using larger mirrors with the exception of the FoV. Although the FoV might be smaller, the stereo region may in fact be larger, because a more effective use of the viewing windows is achieved. Furthermore, the angles between left and re-

flected right windows are minimized for larger mirrors. For these reasons we recommend the use of mirrors with at least the same horizontal size as the display. In practice, the user will have to balance the system parameters in order for the stereo area to enclose all the virtual objects. With the script we have developed, the user can test different mirror and display configurations to select the best option. The angles between left and reflected right windows might have an impact on other depth cues such as convergence and accommodation. To minimize this problem, configurations with lower angles should be used. These depth cues have a rather low strength in comparison to binocular disparity [CV95]. In fact, just by using smaller display sizes with the same mirror to change the angles we can still have a very strong depth sensation with large angles.

A limitation of our system is that it is only developed for DVR. If rectangular stereo images are available, they cannot be directly used because one of the images needs to be skewed (Fig. 2). For our main purpose, visualization of stereo medical volumes, our system fulfils most of the relevant criteria and can compete with traditional systems.

In the medical area, some evaluations of stereoscopic systems were performed. Some even go back as far as 1990 [OO90], and a more recent performed by radiologists comparing different 3D systems can be found in [TSO*12]. Several works in the visualization literature suggest that by using stereopsis, we increase greatly the understanding of depth [HWSB99], [HHM98], in particular for medical datasets [KSTE06]. It should, however, be pointed out that the usage of stereopsis is very task-dependent [WT05].

If collaboration is required two scenarios are possible, the first is to duplicate the system and render the same stereo pairs (simply by duplicating the screens) and second by allowing one user at a time to view the scene. The last scenario is similar to microscope visualization, traditionally found in biology, where different users view at a time an image using a microscope. An alternative scenario is also possible, where one user views the stereoscopic view and the remaing a monoscopic view.

Stereoscopic display systems play an important role in the study of depth perception. In such perception studies it is important to reduce visual fatigue due to flickering effects and produce sharp stereo pairs (with no significant color changes and no ghosting). By eliminating these artifacts, possible confounding factors are discarded. To solve this problem, we selected one system that does not suffer from these artifacts (dual monitor system) and simplified it. By doing so the costs of the system are reduced and a smaller physical space is required in the room. Also in the dual-monitor systems the user has to place his eyes at a certain angle, although it is possible to compute this angle in practice it is rather hard to place the user in the right position. In our system the user looks straight at the display avoiding this problem.

This system has been used to study depth perception of enclosed objects [MS13]. In this case, it is important that the objects in the scene are perceived in their correct spatial position. The results of our previous study demonstrate that with appropriate DVR rendering methods, the users are rather accurate in this task, enabling the system to be used for medical purposes, e.g. to view the location of a tumour inside the brain. Small errors in eye position (due to head movements or different interpupillary distance between subjects), mirror or display positions might occur, but within a small range, the visual system is rather good to compensate for them. In fact, by simply changing the angle of the mirror we can still have a strong stereo sensation with large incorrect angles, but this will affect the correct spatial position of the objects and will make it more difficult to perceive stereo until the effect completely breaks down. The results of this previous study were consistent across participants with high scores of accuracy in perceiving objects spatial position; thus the system is well designed for depth peception even in the presence of small eye position errors. If this would not be the case, our previous study would not have produced consistent results.

The previously reported single monitor system: http://stereo.jpn.org/eng/stphmkr/mirror/mirrorview.htm was not designed for DVR and only provides an approximation of the correct geometry; thus it cannot be used in cases where the spatial position of objects is critical.

We use our stereo system mainly with wide screen monitors, but smaller screens like popular pad systems can be considered. Here, the limitation is the human focal length, approximately 20−24 mm [Gra68], [Sac04].

We have designed the stereoscopic system mainly for stereoscopic visualization of DVR images, but it is possible to make it general purpose if we consider rendering of polygons using off-axis projection that requires a non symmetric camera frustum, by OpenGL in a similar fashion as presented in [Bou99], [MM05].

In Fig. 2 we present the real prototype of the stereo system. In the display we can see the stereo pair in this case of a segmented brain from a MRI image of the head with a plane of dots in the back. We would also like to mention that the system is easy to assemble and that the additional cost is low (mainly the price of the mirror).

Prolonged usage of the system is problematic due to the fact that the head position is fixed. To reduce this problem, a base to place the chin was constructed, but this is by no means a recommendable ergonomic position. For this reason, the system should be only used for a short period of time.

7. Conclusion

We have presented a new stereoscopic system for visualization of DVR images. The main difference in comparison to

the most similar system [Boh] is the use of only one monitor. We also developed the rendering engine for DVR of volumetric datasets mostly for medical imaging visualization. In spite of certain geometrical constraints, the system may prove useful for medical imaging applications.

Acknowledgment

This work was funded by the Visualization programme of the Swedish Foundation for Strategic Research, the KK Foundation, Vinnova, Invest in Sweden Agency, Vårdalstiftelsen (grant 2009/0079) and the Swedish Childhood Cancer Foundation (grant no. MT2013-0036). The authors are indebted to Torbjörn Gustafsson and Per Carleberg for their contribution in the display construction.

References

[Bar03] BARCO: Stereoscopic projection: 3d projection technology. http://www.barco.com/projection_systems/downloads/barco_stereoscopic_proj.pdf, 2003. 1

[Ber96] BERTHIER A.: Images stéréoscopiques de grand format (in French). *Cosmos 34*, 590 and 591 (May 1896), 205–210 and 227–233. 1

[BES00] BIMBER O., ENCARNAÇÃO L. M., SCHMALSTIEG D.: Augmented reality with back-projection systems using transflective surfaces. *Computer Graphics Forum (Proceedings of EUROGRAPHICS 2000) 19*, 3 (2000), 161–168. 3

[BFSE01] BIMBER O., FRÖHLICH B., SCHMALSTIEG D., ENCARNAÇÃO L. M.: The virtual showcase. *IEEE Computer Graphics and Applications 21*, 6 (2001), 48–55. 3

[Boh] BOHÁČ M.: Dual monitor set−up for stereoscopic viewing. http://klub.stereofotograf.eu/dual_monitor.php. 2, 8

[Bou99] BOURKE P.: Calculating stereo pairs. http://paulbourke.net/miscellaneous/stereographics/stereorender/, 1999. 7

[CV95] CUTTING J. E., VISHTON P. M.: Perceiving layout and knowing distances: The integration, relative potency, and contextual use of different information about depth. "W. Epstein and S. Rogers (eds.), Handbook of perception and cognition", 1995. 1, 7

[DCH88] DREBIN R. A., CARPENTER L., HANRAHAN P.: Volume rendering. *SIGGRAPH Computer Graphics 22*, 4 (1988), 65–74. 3

[Dod04] DODGSON N. A.: Variation and extrema of human interpupillary distance. In *Proc. of SPIE: Stereoscopic Displays and Virtual Reality Systems XI* (2004), vol. 5291, pp. 36–46. 2

[FRM*05] FERGASON J., ROBINSON S., MCLAUGHLIN C., BROWN B., ABILEAH A., BAKER T., GREEN P.: An innovative beamsplitter-based stereoscopic/3d display design. *SPIE Stereoscopic Displays and Virtual Reality Systems 5664* (May 2005), 488–494. 2

[GCC*89] GORDON C. C., CLAUSER B. B. C. E., CHURCHILL T., MCCONVILLE J. T., TEBBETTS I., WALKER R. A.: 1987−1988 anthropometric survey of u.s. army personnel: Methods and summary statistics. tr−89−044. natick ma: U.s. army natick research, development and engineering center., 1989. 2

[Gra68] GRAND Y. L.: *Light, Color and Vision*, second ed. London: Chapman and Hall, 1968. 7

[Hea81] HEATH S. T. L.: *A history of Greek mathematics. Volume II:From Aristarchus to Diophantus*. Oxford: At The Clarendon Press., 1981. 2

[Hen93] HENSON D.: *Visual Fields*. Oxford: Oxford University Press, 1993. 4

[HHM98] HUBBOLD R., HANCOCK D., MOORE C.: Stereoscopic volume rendering. *Proc. Visualization in Scientific Computing '98 6*, 3 (1998), 105–115. 7

[Hol05] HOLLIMAN N.: 3d display systems. http://www.dur.ac.uk/n.s.holliman/Presentations/3dv3-0.pdf, 2005. 1

[HWSB99] HUBONA G., WHEELER P., SHIRAH G., BRANDT M.: The relative contributions of stereo, lighting and background scenes in promoting 3d depth visualization. *ACM Transaction on Computer-Human Interaction 6*, 3 (1999), 214–242. 7

[Ive02] IVES F. E.: A novel stereogram. *Journal of the Franklin Institute 153* (1902), 51–52. 1

[JF03] JORKE H., FRITZ M.: Infitec−A new stereoscopic visualization tool by wavelength multiplexing imaging. In *Proc. Electronic Displays* (2003). 1

[KH07] KONRAD J., HALLE M.: 3-d displays and signal processing. *IEEE Signal Processing Mag. 24*, 7 (May 2007), 97–111. 1, 2

[KSTE06] KERSTEN M., STEWART J., TROJE N., ELLIS R.: Enhancing depth perception in translucent volumes. *IEEE Transactions on Visualization and Computer Graphics 12*, 5 (2006), 1117–1124. 7

[Lev88] LEVOY M.: Display of surfaces from volume data. *IEEE Computer Graphics and Applications 8*, 3 (May 1988), 29–37. 3

[MM05] MARREIROS F. M. M., MARCOS A.: Calculating the stereo pairs of a mirror-based augmented reality system. *13º Encontro Português de Computação Gráfica* (2005). 7

[MS13] MARREIROS F. M. M., SMEDBY Ö.: Stereoscopic static depth perception of enclosed 3d objects. In *SAP '13 Proceedings of the ACM Symposium on Applied Perception* (2013), pp. 15–22. 7

[Nvi12] NVIDIA: 3D Vision. http://www.nvidia.com/object/3d-vision-main.html, 2012. 1

[OO90] OWCZARCZYK J., OWCZARCZYK B.: Evaluation of true 3d display systems for visualizing medical volume data. *The Visual Computer 6*, 4 (1990), 219–226. 7

[Pla] PLANAR3D: 3D Technologies. http://www.planar3d.com/3d-technology/3d-technologies/. 2

[Sac04] SACKETT C.: Survey of optical systems: Phys 531, lecture 11, university of virginia. http://galileo.phys.virginia.edu/classes/531.cas8m.fall04/l11.pdf, 2004. 7

[TSO*12] TOURANCHEAU S., SJÖSTRÖM M., OLSSON R., PERSSON A., RUDLING J., ERICSON T., NORÉN B.: Subjective evaluation of user experience in interactive 3d visualization in a medical context. *Proc. SPIE 8318*, 831814 (2012), 219–226. 7

[WC10] WU H.-H. P., CHANG S.-H.: Design of stereoscopic viewing system based on a compact mirror and dual monitor. *SPIE Optical Engineering 027401 49*, 2 (2010), 1–6. 2

[WT05] WICKENS C., THOMAS L.: Effects of CDTI display dimensionality and conflict geometry on conflict resolution performance. *In Proceedings of the 13th International Symposium on Aviation Psychology* (2005). 7