Crosstalk reduction in passive stereo-projection systems

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Abstract

We describe a scheme for reduction of depolarization artefacts in passive stereo-projection systems. These problems appear due to non-perfectness of stereo-projection equipment: depolarization of the light due to reflection from the screen or due to the passage through the screen, non-ideality of polarizing filters, mixing of left- and right-eye images in a change of relative orientation of the filters, which together produce a strong crosstalk effect, resulting to difficulting stereo-perception. The artefacts are eliminated by software methods, using linear filtering of the image before its projection to the screen. We have implemented this algorithm in VE system Avango [1] by means of texture mappings. All necessary operations are performed by the graphics board, thus providing the real-time rendering rate. The described method considerably improves stability of stereo-perception, making high-quality performances of virtual environment possible on affordable equipment.

Categories and Subject Descriptors (according to ACM CCS): I.3.3 [Computer Graphics]: Bitmap and framebuffer operations, Display and viewing algorithms; I.3.7 [Computer Graphics]: Virtual reality.

1. Introduction

Stereo-projection systems possess a general problem of visual channels crosstalk: the user's left eye receives a small mixture of the image destined for the right eye, and vice versa. As a result, the user observes extra images (ghosts), breaking correct stereo-perception. This problem is present both for active and passive stereo-projection systems [2], but the reasons of its appearance are different. For active stereo the main reasons are phosphor afterglow and leakage through shutter-glasses. The best solution is to use special projectors with short phosphor afterglow time [3]. Additionally, one can reduce the crosstalk using software methods [4,5], by means of pre-processing of the images before their projection to the screen.

In this work we concentrate on the reduction of depolarization artefacts in passive stereo-projection. In section 2 we describe particular features of passive stereo-projection systems. Section 3 presents a method for real-time reduction of artefacts in stereo-images, implemented by us in programming framework Avango [1], and compares it with other existing techniques. Section 4 summarizes the obtained results.

2. Passive stereo-projection

In passive stereo-systems, based on separation of left- and right-eye images by means of polarized light, *linear polarizing filters* are commonly used, producing the light with fixed plane of polarization. Maximal separation of the images in this scheme is achieved at one particular orientation of polarized glasses with respect to filters on the projectors. Deviation from this orientation leads to non-perfect separation of the images, resulting to appearance of ghost images.

Other possibility is the usage of *circular polarizing filters*, which combine the linear filter and quarter-wave plate, whose major optical axes are 45° rotated with respect to each other. In a passage of linearly polarized light through the plate the amplitude vector is decomposed by the optical axes of the plate. The resulting components have different speed of propagation, the width of the plate is chosen in such a way, that the components become $\pi/2$ phase shifted, thus the linearly polarized light is transformed to circular polarization. The advantage of circular polarization usage is a stable separation of the images, independent on user's head orientation. The drawback is that this scheme provides the exactly circular polarization and ideal separation of the images only for one wavelength of the light. For other wavelengths the separation is not complete, this leads to the appearance of colored ghosts.

Besides these effects, there are other artefacts, appearing at the usage of both circular and linear polarization filters, related with non-ideality of the filters and depolarization properties of the screen.

Standard DLP and CRT projectors produce non-polarized light, while the light of LCD-projectors is polarized differently for each color component. Particularly, Toshiba TLP-X20 produce vertically polarized light in red and blue components, and horizontally polarized light in green component. Placing a high-quality linear polarizing filter in front of the projector in such a way, that the major optical axes will be 45° rotated relative to horizon, we force the light to be polarized in one plane for all color components. In standard glasses, used in passive stereo-projection, the filters are also oriented at the angle 45° with respect to the horizon. This scheme can be used for the projectors of all mentioned types, as a result the intensity of light from each projector will be reduced by half.

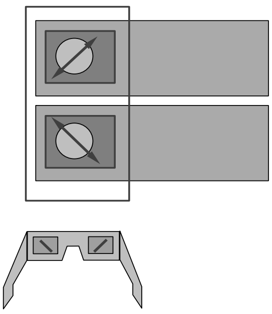


Fig.1. Orientation of the filters in passive stereo-projection system.

The typical properties of screens and polarization filters, commonly used in passive stereo-projection systems, were measured by a calibrated camera, and presented in fig.2 and Table 1. Fig.2 shows the intensities of signal, observed by user, and ghost, appearing as a result of depolarization of the signal on the screen, versus the observation angle θ. This value is defined as the angle between the normal to the screen and direction from the screen to the user, assuming that the light is projected along the normal. Both intensities are normalized by the value of the signal at $\theta = 0$. One can see from this graph that the intensity of the ghost is independent on the angle, satisfying Lambert's law [8], while the intensity of the signal reveals sharp angular dependence with a maximum at $\theta = 0$. This dependence is well approximated by the formula $I \sim \cos^n \theta$, with $n = 7$ for the given screen. The value $\lambda = n+1$ is called Lambertian exponent [9]. The scattering properties of the screen are defined by a microstructure of the surface. More smooth screens, corresponding to smaller microroughness, produce smaller ghosts, but simultaneously have sharper angular dependence for the signal, in the limit ($n \to \infty$) tending to characteristics of mirror surface.

Linear polarizing filters are characterized by transmission coefficients of the light along major optical axes $\eta_{min} = I_{min}/I$, $\eta_{max} = I_{max}/I$, where I is the intensity of linearly polarized light submitted to the filter perpendicularly to its surface, with the plane of polarization directed parallelly to each optical axis, I_{min}, I_{max} are registered intensities of the light passed through the filter. An important characteristics of the filter is extinction ratio $\xi = \eta_{min}/\eta_{max}$. In our case this coefficient directly defines the ratio of ghost and signal intensities for the case of ghosts, caused by non-ideality of the filters. The measurement of this characteristics can be done in non-polarized light, doubling the filters and determining the minimal and maximal intensities of the light passed through both filters, when the filters are rotated one relative to the other. The ratio of minimal and maximal intensities in this case is given by the formula: $I_{min}/I_{max} = (\xi_1 + \xi_2)/(1 + \xi_1\xi_2)$, where $\xi_{1,2}$ are extinction ratios for separate filters. When the identical filters are used, $I_{min}/I_{max} = 2\xi/(1+\xi^2)$.

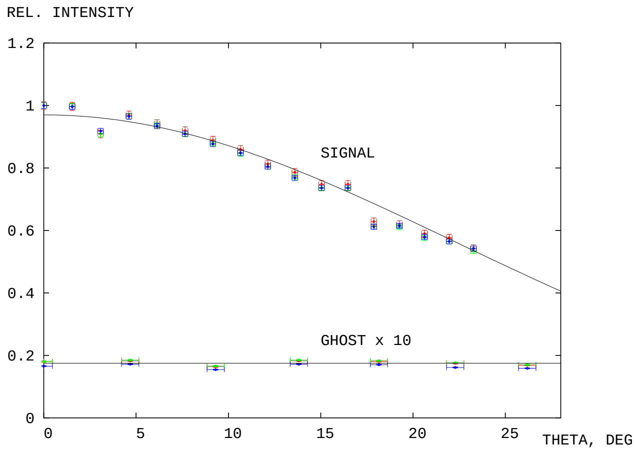


Fig.2. Typical angular dependence of intensity for polarized light reflected from the screen.

	ξ_r	ξ_g	ξ_b
TAN filter	< 0.0006	< 0.0002	< 0.0002
Captain glasses	< 0.006	< 0.003	< 0.002
V-45/135 glasses (carton rim)	0.0174 $\pm$0.0009	0.0115 $\pm$0.0005	0.0363 $\pm$0.0015

Table 1: extinction ratio ξ for different polarizing filters.

The characteristics, measured by this method, are given in Table 1. High quality filters and glasses have smaller ξ, while cheap and widely used glasses with carton rim have larger ξ, leading to appearance of ghosts, particularly strong in blue color component. Besides, in series of cheap glasses considerable dispersion of ξ-values is observed, whose standard deviation in three color components was $(\sigma_r, \sigma_g, \sigma_b) = (0.005, 0.003, 0.0014)$ at mean values $(\xi_r, \xi_g, \xi_b) = (0.011, 0.014, 0.0357)$. To use the technique for ghost compensation described below, one needs either to select the glasses with closer characteristics or to double the glasses, aligning parallel their optical axes (this will considerably decrease the extinction ratio: $\xi \to \xi^2$).

As the performed measurements show, when one uses the high quality filters and glasses, the main origin of the ghosts is depolarization of light on the screen, while for cheaper glasses the non-ideality of polarizing filters makes a contribution, comparable with the depolarization.

Remark: Measurements of polarized light intensity in its passage through specimens and reflection from the surfaces allow to determine not only the coefficient ξ, but also the other optical parameters of the material [10, 11]. These measurements are the base for methods of non-contact control, widely used in the modern industry, medicine etc.

3. The method

We use a basic idea proposed in paper [4]. The image L, destined for the left eye, due to the above described effects receives a small admixture βR of the image, destined for the right eye. To compensate this ghost let's subtract from L an image αR, and symmetrically for the right eye: $L' = L - \alpha R$, $R' = R - \alpha L$. In this case the image observed by user will be:

$$L' + \beta R' = (1 - \alpha\beta)L + (\beta - \alpha)R,$$
$$R' + \beta L' = (1 - \alpha\beta)R + (\beta - \alpha)L.$$

At $\alpha = \beta$ the ghost is eliminated, and the image observed by user becomes proportional to the original (L, R) with coefficient $(1 - \alpha^2)$, close to unity for small α.

We have implemented this method in Avango VE system [1], based on Performer [7] graphics library. Avango's object *fpScreen*, supporting the interface to Performer's object *pfChannel*, defines a region of the frame buffer (channel) in the graphics board, where the image output is directed. Passive stereo-setups use two channels, marked on fig.4 as *ch1* and *ch2*, which render the images for the left and right eyes. Both channels render the same main scene graph, representing user defined model, and attached to the *scene-root* node. This structure of graphical renderer is defined in a standard Avango's configuration file *av-passive-stereo-wall.scm*.

Channels differ by the settings of view-transform, which is defined by known parameters, as the size of the screen, position of projectors and user's viewpoint, stereobase etc, specified in a calibration file *av-passive-stereo-wall-calib.scm*. We modify the standard configuration in the following way.

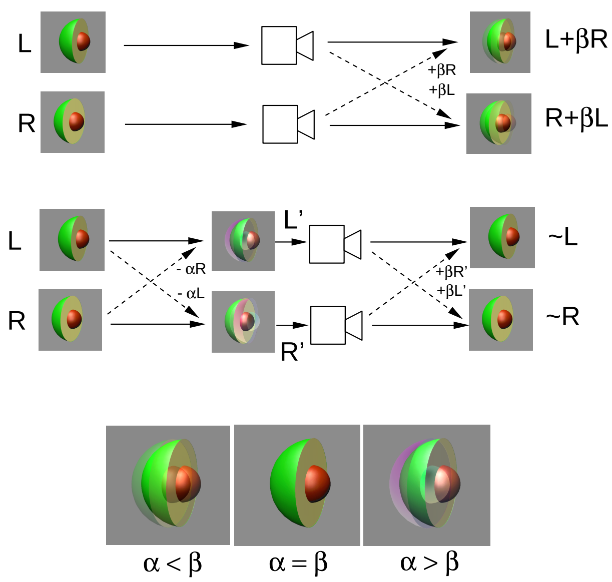
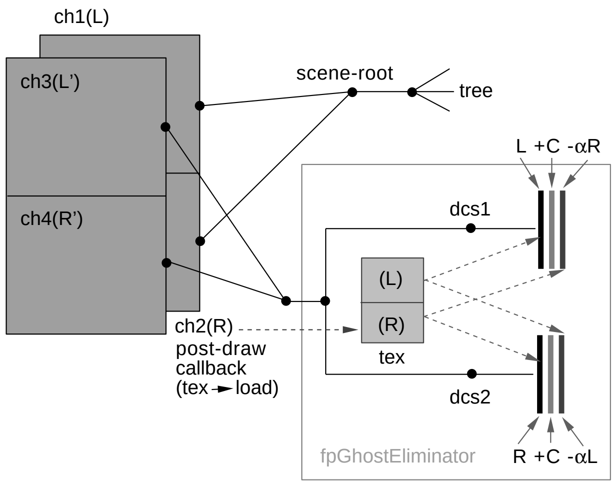


Fig.3. Ghosts elimination: an idea.



layer	texture	material	transparency
L, R	*tex*	$(1,1,1,1)$	no
$+C$	no	$(r_0, g_0, b_0, \alpha_0)$	additive
$-\alpha L, -\alpha R$	*tex*	$(r_i, g_i, b_i, \alpha_i)$	subtractive

Fig.4. Ghosts elimination: implementation.

In the channel *ch2* a post-draw callback is activated, which loads the frame buffer content into a texture *tex*. Because the frame buffer and the texture are located in the graphics board, we avoid slow procedures of data copying from the graphics board to the main memory. Loaded texture is used in an auxiliary scene graph, which is rendered by two additional channels *ch3, ch4*. These channels geometrically correspond to the same regions of the frame buffer, as *ch1, ch2*. The auxiliary scene graph defines for each eye three superimposed square primitives (quads):

- L, R quads carry the texture *tex* with the copy of the frame buffer.
- $+C$ semi-transparent quads possess a constant color: $\text{Color}_0 = (r_0, g_0, b_0, \alpha_0)$, which is added to L, R-images, making possible later subtraction. Such addition is required for the scenes, which have black background, contain black objects, or the objects with a small intensity in at least one of the color components. As a result, the image observed by user receives an addition $(1+\beta)\text{Color}_0$, slightly reducing the overall contrast of the image. Impossibility to preserve an absolutely black background in applications is a restriction of the given method.
- $-\alpha L, -\alpha R$ quads are rendered using special type of transparency (subtractive), available in OpenGL, which allows to perform the necessary subtraction of the ghosts. The quads have own color: $\text{Color}_i = (r_i, g_i, b_i, \alpha_i),\ i = 1, 2$, which is multiplied componentwise to the content of the texture *tex*. This is equivalent to an introduction of different α-constants for different color components, giving a possibility to compensate colored artefacts.

Matrices *dcs1,2* control the position of the quads and are defined in such a way, that the images in channels *ch3,ch4* exactly match the images of *ch1,ch2*. The auxiliary scene graph, containing six primitives only, is rendered fast, so that the full rendering of four channels has the same framerate as in the standard configuration (assuming that fill rate of the graphics board is sufficient). The described scheme is implemented in a modified configuration file, and is activated by an additional option passed to the viewer:

```
aview -o device:passive-stereo-wall \
-o ghost-elimination:1
```

Remarks:

1. The modification does not affect other components of virtual environment, such as navigation and interaction. The user sees the result of auxiliary scene graph rendering, exactly superimposed on the result of main scene graph rendering, navigating in the model space and interacting with the objects, assigned to the main scene graph, not observing any geometrical discrepancies.

2. This scheme requires the exact geometrical alignment of the projected L, R-images. The errors in alignment are visible as artifacts along the edges of the objects. However, as our experience shows, the necessary precision can be easily achieved using standard calibration methods (e.g. using grids produced by `screentest` program).

3. To achieve complete compensation of ghosts exact γ-correction of the projection system is required. The ghosts, created by physical effects (for passive systems - by depolarization, for active ones - by phosphor afterglow), are linearly dependent on the signal, their compensation by means of the described method is also linear, thus the projection system should possess the linear characteristics ($\gamma = 1$) in each color component to achieve the complete compensation.

4. For the scenes with a bright background the ghosts, as a rule, are less noticeable. This effect has the following explanation: at a fixed value of the signal and the ghost corresponding to it, the ghost intensity *relative to the background* becomes smaller for brighter background. As the physiological investigations [12] show, visual perception in a wide range of intensities satisfies Weber's law, see fig.5: $\Delta I / I = Const$, where ΔI is lowest perceivable difference of intensity at the mean value of intensity I. Due to this fact a suppression of ghosts is possible by increasing the brightness of the background.

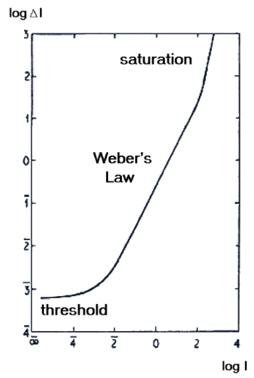


Fig.5. Eye's sensitivity curve [12].

However, our experiments show that too bright backgrounds are needed for such suppression. The method of ghosts subtraction described here allows to compensate the ghosts also for the sufficiently dark background, whose intensity is higher than the intensity of the ghosts.

Possibility for further extensions:

1. The developed program module allows to compensate the ghosts with different color settings separately for each eye. This is done to compensate the ghosts, related with the color difference of the projectors and small rotation of the filters relative to their optimal position. Linear color corrections of general form are also possible, using OpenGL color matrix transformations. These corrections can be used to compensate color distortions of the systems, based on the technique of color shifting [13].

2. The described scheme can be easily modified for compensation of geometrical distortions, appearing e.g. in projections onto curved screens. For these purpose the auxiliary textures should be subjected to corresponding non-linear transformations. Certain corrections in the interaction model are also needed in this case.

3. The described scheme is directly applicable for passive stereo-projections. In active systems similar scheme can be used, copying the content of the L, R stereo frame buffer components to the textures.

4. User's head rotation to large angle destroys the stereo-perception. This problem exists for all stereo systems, both active and passive, and has the following geometrical reason. The images, destined for the left and right eyes are separated on the screen in horizontal direction, and after user's head rotation do not match each other, as a result the stereo perception is lost. The tracking systems can remove this problem for a restricted number of users, adjusting the direction of image separation to the actual position of the user head. However, in this case the stereo perception for non-tracked user will break not only due to rotation of her/his own head, but also due to rotation of the other user head, whose orientation is tracked. As the experience shows, the stereo perception is preserved for small (10°) rotation of the head relative to the optimal position, this fact makes possible stereo presentations for large audience.

5. For passive systems there is one more problem besides the geometrical one: dependence of ghost intensity on the head orientation. Our scheme allows to change coefficients of compensation dynamically, following the head orientation measured by the tracking device, so that the ghosts can be compensated for separate users in a restricted range of rotation angles. When the circular polarizing filters are used, the signal is almost independent on the orientation of the head, but the colored ghosts, related with the impossibility to provide the exactly circular polarization for all wavelengths (see above), possess strong angular dependence. For complete compensation of such ghosts the tracking systems are also required.

Comparison with other techniques

The idea to subtract the ghosts before the projection of images to the screen was originally proposed in paper [4]. The implementation, described in [4], differs from our one in the following key aspects. The subtractional formula, chosen in [4], is essentially non-linear in terms of the source pixel intensity. This computation is not supported by the existing graphics boards, requires additional CPU power and cannot be performed at real-time frame rate. The approach [4] addresses the crosstalk problem for active stereo systems, possessing certain specific features, such as non-uniformity of the light leakage through the shutter glasses in the image field. The technique [4] includes a large set of heuristic parameters, complicating the adjustment of the algorithm to a particular type of the display system.

The paper [5] describes an alternative implementation for the same idea. It presents a software ghosts compensation in active stereo systems, based on a non-linear formula, where the participating functions were found in psycho-physiological measurement. The result collected to a lookup table is used for image correction. However, the required operations are time-consuming and are not supported by current graphics boards as well. This fact limits the possible implementation of the method to off-line video pre-processing. Besides, the papers [4, 5] do not take into account the dependence of the method on γ-value of the display, while most significant non-linear effects in the considered problem are related with this value.

One more implementation of the same idea is patented in [6] hardware modification of the display system. In this implementation the necessary linear filtering of the signal is performed by means of an electric circuit, inserted between two LCD panels, used in an autostereoscopic display. The circuit includes special elements provided for hardware γ-correction of the system.

In our paper we have measured the contribution of various effects to the crosstalk in passive stereo projection systems. These effects are linear in terms of signal intensity, and require the linear methods for compensation. In our implementation this compensation is performed completely by the graphics board using standard OpenGL and the systems build on the top of it. By these means the real-time processing rate is achieved, necessary for the applications of virtual environment.

4. Summary

This paper describes the scheme for reduction of depolarization artefacts in passive stereo-projection systems, difficulting stereo-perception. These problems appear due to non-perfectness of stereo-projection equipment and can be eliminated by software methods. We have described the particular features of passive stereo-projection systems, which consist of inexpensive components and are most convenient for creation of multiuser large-scale virtual environments. These systems are usually based on separation of the images by means of light polarization, and the typical problems for them are depolarization of the light due to reflection from the screen or due to the passage through the screen, non-ideality of polarizing filters, mixing of left- and right-eye images in a change of relative orientation of the filters, appearing e.g. due to the rotation of user's head with respect to the optimal position. These problems can be partially removed by the tracking of the user's head orientation, by the usage of high quality filters and screens made of special materials, possessing minimal depolarization properties. Then we have described a software method for the reduction of the remaining ghosts, based on pre-filtering of the image before its projection to the screen: $L' = L + C - \alpha R$, $R' = R + C - \alpha L$, where L, R are images, destined for the left and right eye respectively, α, C are constants. The intensity of the ghost, created by the described physical effects, depends on the intensity of the original image linearly, with the coefficient β. At the choice $\alpha = \beta$ the ghost is completely compensated. The necessary conditions for such compensation are exact ad-

justment of linearity for the projection system (γ-correction) and support of non-negativeness for L', R' in the whole image area by means of C-parameter adjustment in the formula above. Due to the difference of ghost intensities for different color components the α-coefficients for each component should be adjusted separately. This algorithm is implemented in Avango VE system using texture mappings. All necessary operations are performed by the graphics board, thus providing the real-time rendering rate.

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