SPATIO-ANGULAR SHARPENING FOR MULTIVIEW 3D DISPLAYS

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ABSTRACT

In this paper, we analyze the reproduction of light fields on multiview 3D displays. A two-way interaction between the input light field signal (which is often aliased) and the inter-view light leakage in modern multiview 3D displays is characterized in the joint spatio-angular frequency domain. Reconstruction of light fields by all physical 3D displays is prone to light leakage. This means that the reconstruction low pass filter implemented by the display is too broad in the angular domain, which causes loss of image sharpness. The combination of the 3D display point spread function and human visual system provides the narrow band low pass filter which removes spectral replicas in the reconstructed light field on the multiview display. The non-ideality of this filter is corrected with the proposed prefiltering technique.

1. INTRODUCTION

Multiview 3D displays admit realization of stereoscopic 3D images from any viewpoint without special glasses. In a multiview 3D display, a continuous light field is recovered from a set of 2D camera images that forms angular samples (views). A parallax barrier or lenticular sheet is placed at a small distance in front of the LCD screen. Together, the combination of the LCD screen and the barrier or lenticular sheet reconstructs a continuous light field. It has been shown that a slanted barrier or lenticular helps reduce the so-called "picket fence" or "flipping views" effect (see [3]). This setup enables easier angular interpolation between adjacent samples (views), giving a smooth visual effect for the reconstructed light field. However, one main drawback of the slanted barrier or lenticular arrangements is that they are prone to light leakage that results in a reduction of image sharpness. This is due to the low-pass properties of the display's angular point spread function (PSF) resulting from the physical design. Henceforth, we use the terms light leakage and angular PSF interchangeably.

The interaction between the input light field signal and the inter-view light leakage on the physical display complicates reconstruction analysis. Artifacts in 3D displays are often severe, examples of which includes inter-view blur and double edges. Existing studies of light leakage [1] and light field aliasing due to joint spatio-angular sampling [2, 6] have treated these problems as disjoint and therefore provided an incomplete description. The light leakage between views has been referred to previously as monocular crosstalk [1, 4].

In this paper, we pose the continuous light field recovery formally as a "reconstruction" of the joint spatio-angular signal based on a decomposition of the subsampled or discretized light field signal (in the form of a set of discrete input views) as the principal spectrum and its replicas. Under this formulation, the narrow band low pass reconstruction filtering is carried out by a combination of human visual system and the physical display hardware. Our aim is to show that the light leakage problem stems from the nonidealities of the reconstruction implementation—we do so by analyzing the interaction between the display's spatio-angular point spread function (PSF) and joint spatio-angular aliasing.

Besides the theoretical contributions, we experimentally measure the joint spatio-angular PSF of commercially available multiview 3D displays based on a slanted parallax barrier as well as lenticular prints [3]. Our measurements show significant inter-view light leakage. Based on the experimentally measured light leakage, we develop display dependent filters and also show improved image quality on displays based on parallax barriers and lenticular sheets.

Previous work:

To date, analysis of light field sampling and reconstruction has drawn from joint spatio-angular modeling in frequency domain [2] and union of cosets for analyzing non-rectangular spatio-angular sampling grids [7]. These modeling paradigms give rise to antialiasing schemes using signal processing techniques [6] and lattice theories [7]. Though these antialiasing filters prove effective for idealized multiview 3D displays, they do not handle nonidealities such as light leakage due to the angular PSF of the physical displays.

Previous studies of light leakage have reported that it is responsible for spatial blurring and double edge artifacts. To correct these problems, existing solutions have applied spatial processing to control each view [4, 1]. Owing to the fact that joint spatio-angular aliasing [5] and inter-view/angular correlation are ignored, however, these approaches are inadequate for reducing double edge artifacts and counterbalancing angular blur. The light leakage between views also has

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the effect of lessening the aliasing artifacts such as double edges, which arise when a light field is reconstructed from a set of undersampled views. Although this phenomenon was reported previously, the analysis we provide below is contrary to the prior work in this area. Specifically, in the work of Jain et al. [4], light leakage is analyzed as a spatial phenomenon. However, as the term "crosstalk" implies, the correct representation should take into account light leakage and aliasing artifacts in the joint spatio-angular domain, as is done here.

2. ANALYSIS OF MULTIVIEW 3D DISPLAYS

2.1. Sampling and Aliasing

Below, the interactions between the input light field signal, sampling, and light leakage due to the display PSF are analyzed. We do so by the way of joint spatio-angular modeling [2, 5] (used earlier to model light fields). The relation between the depth and frequency content in the joint spatial-angular domain, and the sampling and reconstruction of light fields is analyzed by Chai et al. [2]. This representation was adopted by Zwicker et al. [5] to analyze the sampled light field in multiview 3D displays, which we state below.

Suppose the 3D display reproduces only horizontal parallax (see [5]). In this case, the light rays emitted from a single scan line of a horizontal parallax are parameterized using t, the angular coordinate as specified by the parallax barrier or lenticular plane index, and v the (horizontal) spatial coordinate of the high resolution screen. Owing to the fact that angular component of stereoscopic image is uniquely determined by the depth of the object in focus, the Fourier transform of the light field $x(v, t)$ is highly structured, as shown in figure 1(a).

For the sampled light field, denote by Δt and Δv the angular and periodic spatial sampling intervals, respectively. By the Poisson summation formula, the spectrum of the discretized light field signal x_d is *a sum of modulated signals*:

$$\hat{x}_d(\Omega_v, \Omega_t) = \frac{1}{\Delta v \Delta t} \sum_{\lambda_v \in \frac{2\pi}{\Delta v}\mathbb{Z}} \sum_{\lambda_t \in \frac{2\pi}{\Delta t}\mathbb{Z}} \hat{x}\left(\Omega_v - \lambda_v, \Omega_t - \lambda_t\right).$$

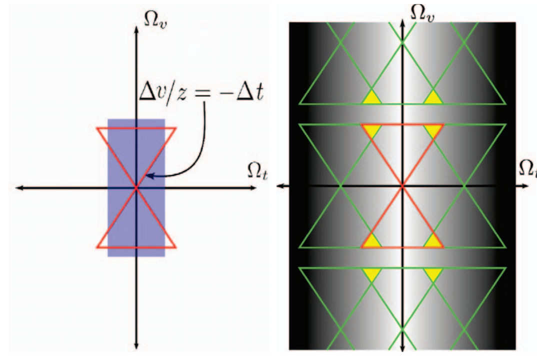
The *display bandwidth* in the joint spatio-angular domain (blue box in Figure 1(a)) is determined by the Nyquist limit:

$$\hat{h}(\Omega_v, \Omega_t) := \begin{cases} 1 & \text{if } |\Omega_v| \leq \pi/\Delta v, |\Omega_t| \leq \pi/\Delta t \\ 0 & \text{otherwise} \end{cases}. \quad (1)$$

This sheds light on the possible joint spatio-depth resolution of the light field on a given display. Signals with frequency content beyond the display support appear aliased.

2.2. Interaction of Aliased Lightfield and Light Leakage

The overall goal of light field reconstruction is to recover a *continuous* light field x from a set of samples. This is realizable as reconstruction —the process of separating the principal spectrum from its replicas by the way of narrow band low pass filtering. From a signal processing point of view, the slanted barrier is an implementation of an angular low pass reconstruction filter, which removes spectral replicas in the angular domain. This nonideal 3D angular reconstruction blur kernel also leads to inter-view light leakage.



(a) Original signal (b) Aliased, with angular PSF

Fig. 1. Spectral support for the light field and angular PSF. Red and green lines represent the support of principal and replicated spectra, respectively. Aliased regions are yellow; display bandwidth is blue. The angular PSF is overlaid in (b).

In this section, we analyze the trade-offs between stereoscopic image reconstruction and light leakage. When the smoothing is (angular) translation invariant, this phenomenon is modeled precisely by an angular point spread function $f(t)$ acting on the subsampled light field x_d regardless of the spatial context of the signal. By the separability of the Fourier transform and the convolution theorem, the overall effect is:

$$\{\hat{f} \cdot \hat{x}_d\} = \frac{1}{\Delta v \Delta t} \sum_{\lambda_v \in \frac{2\pi}{\Delta v}\mathbb{Z}} \sum_{\lambda_t \in \frac{2\pi}{\Delta t}\mathbb{Z}} \hat{f}(\Omega_t)\hat{x}\left(\Omega_v - \lambda_v, \Omega_t - \lambda_t\right). \quad (2)$$

Figure 1 (b) shows the grayscale coded frequency response of a typical light leakage kernel f, which is inherently lowpass, i.e. darker shades indicate greater attenuation. The spectral replica due to modulated light field $\hat{x}\left(\Omega_v - \lambda_v, \Omega_t - \lambda_t\right)$ is attenuated heavily, thanks to the modulation by high frequency λ_t and the rapid decay of the low-pass frequency response $\hat{f}(\Omega_t)$. Indeed, the double edge aliasing artifacts are softened. The baseband signal $\hat{x}(\Omega_v, \Omega_t)$ is "smoothed" by the angular PSF $\hat{f}(\Omega_t)$, however—effect of which is an inter-view blurring that results in diminished depth discrimination and a spatial blurring effect. As a result of this spatial blurring effect, the light field reconstructed on the display looks washed out and loses sharper spatial details such as sharp spatial edges and fine textures. Although double edge artifacts appear less pronounced, aliasing is not completely removed by light leakage due to the angular PSF. Therefore, proper reconstruction requires a combination of antialiasing and angular sharpening. Angular sharpening means suitable prefiltering of the light field signal to compensate for the low-pass characteristic of the angular PSF of the 3D display.

3. ANTIALIASING AND ANGULAR SHARPENING STRATEGIES

To reconstruct the continuous light field x, we propose a prefiltering approach to address the joint problem of aliasing and light leakage. Define $g(v)$ to be a combination of the LCD spatial blur kernel and the spatial smoothing kernel inherent in human visual system. Let the prefilter $\theta(v,t)$ minimize the error between the continuous light field $\{g \star x\}(v, t_0)$ and the reconstructed light field $\{g \star f \star (\theta \star x)_d\}(v, t_0)$, where $\cdot_d$ denotes discretization and $\star$ is convolution. The reconstruction error E_R is:

$$E_R = (\{\hat{g} \cdot \hat{f} \cdot \hat{\theta}\} - \hat{g})\hat{x} + \sum_{\substack{(\lambda_v,\lambda_t)\\ \neq(0,0)}} \hat{g}(\Omega_v)\hat{f}(\Omega_t)\{\hat{x} \cdot \hat{\theta}\}(\Omega_v - \lambda_v, \Omega_t - \lambda_t)$$

Here the first term measures fidelity since it tries to minimize the error between the true signal the signal which is actually seen. The second term is the energy of the non-principal spectral replicas, which needs to be minimized. A non-parametric approach to designing $\hat{\theta}$ is to minimize the cost function

$$J := \|\{\hat{g} \cdot \hat{f} \cdot \hat{\theta}\} - \hat{g}\|^2 + \sum_{\substack{(\lambda_v,\lambda_t)\\ \neq(0,0)}} \|\hat{g}(\Omega_v)\hat{f}(\Omega_t)\hat{\theta}(\Omega_v - \lambda_v, \Omega_t - \lambda_t)\|^2.$$

Setting $\partial J / \partial \hat{\theta}(\Omega_v, \Omega_t)$ to zero and solving for $\hat{\theta}$, the L^2 optimal prefiltering takes the form of

$$\hat{\theta}_{\text{opt}}(\Omega_v, \Omega_t) = \frac{|\hat{g}^2(\Omega_v)\hat{f}(\Omega_t)|}{\sum_{\lambda_v,\lambda_t} |\hat{g}(\Omega_v - \lambda_v)\hat{f}(\Omega_t - \lambda_t)|^2}. \qquad (3)$$

Supposing that the spatial sampling is sufficiently dense and $g(v)$ and $f(t)$ have sufficiently sharp cutoff, then, $\{\hat{g} \cdot \hat{f}\} \approx \hat{f}(\Omega_t)\hat{h}(\Omega_v, \Omega_t)$ where $\hat{h}$ is the ideal low-pass filter of (1). Then it follows that antialiasing and angular sharpening in $\hat{\theta}_{\text{opt}}$ are *separable*: $\hat{\theta}_{\text{opt}}(\Omega_v, \Omega_t) = \hat{h}(\Omega_v, \Omega_t)/|\hat{f}(\Omega_t)|$ This implies that one could first antialias the input light field and then perform a prefiltering step (to counter the display's angular PSF) before the continuous light field is reconstructed on the display.

4. ANGULAR PSF MEASUREMENT AND RESULTS

Following a procedure similar to the one described by Jain et al. [4], we measured the angular point spread function of a 5-view Newsight 32 inch parallax barrier multiview display and an 8-view Alioscopy 22 inch lenticular display. The displays were configured to show an "angular impulse function" $x(v,t) = \delta(t)$ by setting one view to a solid red and all others to black. The light leakage then is observed by cameras positioned to see all views from suitable viewer distance. The 1D angular PSF for the parallax barrier and lenticular displays was measured as $f(\Delta t \cdot m) = [0.548, 0.666, 1.000, 0.666, 0.548]$ and $f(\Delta t \cdot m) = [0.59, 0.67, 0.78, 1.000, 0.78, 0.67, 0.59]$.

The results are obtained using the separable filter approach mentioned above. The angular sharpening filter (after the antialiasing step) for parallax barrier and lenticular displays are $\tilde{f}(\Delta t{\cdot}m) = [-0.036, -0.40, 1.00, -0.40, -0.036]$, $\tilde{f}(\Delta t{\cdot}m) = [0.053, -0.14, -0.383, 1, -0.383, -0.14, 0.053]$ respectively. These filters are designed as the pseudo-inverse of f. The antialiasing component was implemented according to the model of Zwicker et al. [5]. For antialiasing, the input light field was highly upsampled to remove angular aliasing and filtered using a 1D angular Gaussian filter. Figures 2 and 3 show results for the lenticular display and the 'Elephant 2' light field. We observed that the proposed method yields better result compared to previous approaches. More results and subjective tests are at: `http://videoprocessing.ucsd.edu/~vikas/icassp10/`

5. CONCLUSION

In this work, a two-way interaction between the light field signal and the inter-view light leakage in multiview 3D displays is modeled in the spatio-angular domain. Light field recovery is cast as a problem of spatio-angular reconstruction, where the display and human visual system provide the narrow band filter. The nonidealities of this filter are corrected with the proposed scheme, which addresses aliasing and angular PSF. We confirmed our approach in theory and on real displays, and showed improvement over existing methods.

6. REFERENCES

[1] A. Boev, K. Raunio and K. Egiazarian, "Gpu-based algorithms for optimized visualization and crosstalk mitigation on a multiview display," *Proc. SPIE (2008),* vol. 6803, pp. 1 - 12.

[2] J. Chai., X. Tong, S.C. Chan and H. Shum, "Plenoptic sampling," *ACM SIGGRAPH '00,* 2000, pp. 307 - 318.

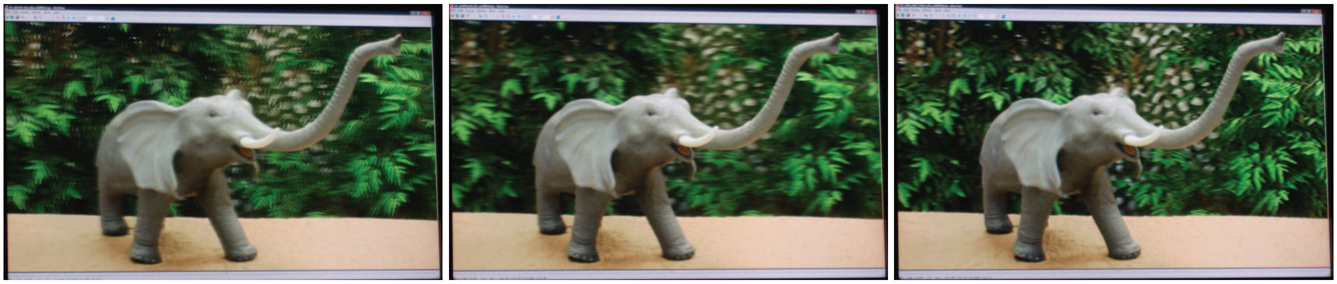
[3] Van Berkel et. al, "Characterisation and optimisation of 3d-lcd module design," *Proc. SPIE,* 1997, vol. 3012, pp. 179 - 187.

[4] A. Jain and J. Konrad, "Crosstalk in automultiscopic 3-D displays: Blessing in disguise?" *Proc. SPIE,* 2007, vol. 6490, pp. 1 - 12.

[5] M. Zwicker et al., "Antialiasing for automultiscopic 3D displays," *Eurographics Symposium on Rendering,* 2006.

[6] M. Zwicker et al., "Display pre-filtering for multi-view video compression," *ACM MULTIMEDIA 07,* 2007, pp. 1046 - 1053. *ACM SIGGRAPH 96,* 1996.

[7] J. Konrad et al., " Subsampling models and anti-alias filters for 3-D automultiscopic displays," *IEEE Trans. on Image Processing,* 2006.

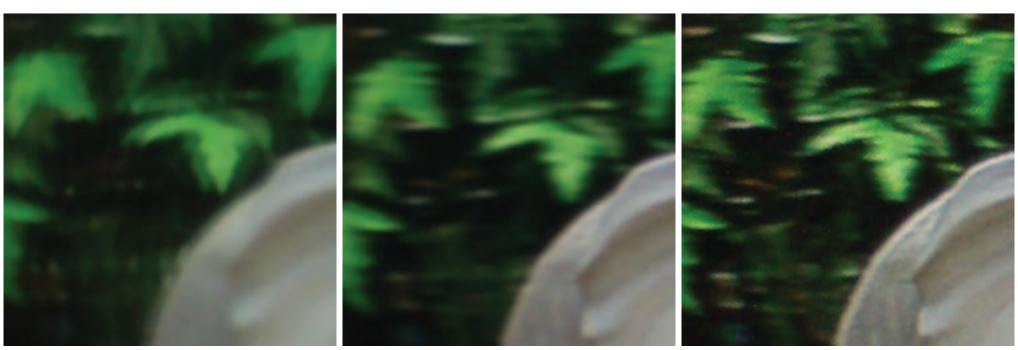


(a) No processing (b) With antialias filter [5] (c) With proposed prefilter

(d) No processing (zoomed) (e) With antialias filter [5] (zoomed) (f) With proposed prefilter (zoomed)

Fig. 2. Screen capture of “Elephant 2” image, shown on a lenticular 3D display. Figs. (a) and (d) show the angular aliasing (double image) artifacts. Fig. (b) and (e) show the antialiased light field.(no double images, blurry due to angular PSF). Figs. (c) and (f) show the proposed antialiasing plus presharpening.

(a) Method by Boev et al. [1] (b) Prefilter by Jain et al. [4] (c) Proposed prefilter



(d) Method by Boev et al. [1] (zoomed) (e) Prefilter by Jain et al. [4] (zoomed) (f) Proposed prefilter (zoomed)

Fig. 3. Comparison of different filtering schemes for the “Elephant 2” image. Figs. (a) and (d) show the scheme by Boev et al. [1] (double images remain). Figs. (b) and (e) shows the scheme by Jain et al. [4]. Regions away from the zero depth plane are blurry. Figs. (c) and (f) show the proposed scheme, all regions appear sharper.