SPATIO-TEMPORAL FREQUENCY ANALYSIS OF MOTION BLUR REDUCTION ON LCDS

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ABSTRACT

Liquid Crystal Displays (LCDs) are known to suffer from motion blur. In this paper, motion blur on LCDs is analyzed by examining the spatio-temporal spectrum of the perceived picture. This analysis is used to examine the performance of two motion blur reduction techniques: Smooth Frame Insertion (SFI) and Motion Compensated Up-conversion (MCU). The performance of both techniques is compared for TV applications.

***Index Terms*—** Dynamic resolution, frame rate conversion, LCDs, motion blur, video enhancement, video processing.

1. INTRODUCTION

The picture quality of motion pictures, shown on a display, is the product of processing a light signal through a cascade of signal capturing, storing, transmission, and reconstruction. The Human Visual System (HVS), however, determines the *perceived* quality of the displayed motion pictures. For *optimal* perception, i.e. indistinguishable from the original, the HVS should be the limiting factor in all process stages for all quality aspects such as resolution, brightness, and colorfulness.

For TV applications, spatial (static) resolution has seen a recent jump in performance with the introduction of HDTV and the availability of large format LCDs at consumer price levels. LCDs, however, are known to perform poorly with respect to temporal resolution, causing visible spatial blur whenever video contains motion [1]. This low temporal resolution is a result of the temporal response of the display, defined by the LC material response, the hold characteristic of the active matrix, and the backlight.

In order to reduce motion blur on LCDs its temporal resolution needs to be improved. This is achieved by reducing the response time of LCDs and by reducing the hold time of the display. As such, in the past, improvements have been developed in the area of LC switching behavior [2], pixel layouts, and driving schemes [3], yielding a reduction of the response time to a few milliseconds. Also several hold time reduction methods have been reported in literature including scanning backlight [4], black frame insertion [5], gray frame insertion [6] (also known as pseudo impulse driving), SFI [7], and MCU [8].

In this paper, the latter two motion blur reduction methods are analyzed and discussed in more detail, as they are most suitable for TV applications [9]. A frequency analysis of motion blur on LCDs is given in Section 2. This analysis is used to discuss the performance of SFI, in Section 3, and MCU, in Section 4. Advantages and disadvantages of both methods are compared in Section 5 and final conclusions are drawn in Section 6.

2. MOTION BLUR

In order to appreciate how the temporal response of video reconstruction on a display causes a perceived spatial attenuation of high frequencies, consider a video signal $I_c(\vec{x},t)$ that is sampled and reconstructed, as indicated in Eq. 1 and explained in detail in [10].

$$I_d(\vec{x},t) = (I_c(\vec{x},t)\cdot\Lambda(\vec{x},t)) * A(\vec{x},t), \qquad (1)$$

where $I_d(\vec{x},t)$ is the displayed (or reconstructed) video signal, $\Lambda(\vec{x},t)$ the spatio-temporal sampling grid, and $A(\vec{x},t)$ the reconstruction aperture of the display. Furthermore, video containing a motion $\vec{v}$ is denoted as:

$$I_m(\vec{x},t) = I_c(\vec{x}+\vec{v}t,t), \quad \text{or} \qquad (2)$$

$$I^f_m(\vec{f}_x,f_t) = I^f_c(\vec{f}_x, f_t - \vec{v}\cdot\vec{f}_x) \qquad (3)$$

in the time and frequency domain, respectively. The pursuit of this motion by the HVS, known as eye-tracking, corresponds to a transformation of coordinates of the reconstruction signal, yielding the video signal after eye-tracking, $I_e(\vec{x},t)$, as indicated in Eq. 4.

$$I_e(\vec{x},t) = I_d(\vec{x}-\vec{v}t,t) \quad \text{or} \qquad (4)$$

$$I^f_e(\vec{f}_x,f_t) = I^f_d(\vec{f}_x,f_v), \qquad (5)$$

with $f_v = f_t + \vec{v}\cdot\vec{f}_x$. Combining the above, yields Eq. 6:

$$I^f_e(\vec{f}_x,f_t) = \left(I^f_c(\vec{f}_x,f_t) * \Lambda^f(\vec{f}_x,f_v)\right) A^f(\vec{f}_x,f_v). \qquad (6)$$

It illustrates that the temporal component of the aperture, A^f, is a function of motion $\vec{v}$.

$I_e(\vec{x},t)$ equals the signal on the retina. The *perceived* video signal, however, is approximated by taking into account that the HVS is only sensitive to low temporal and spatial frequencies. As such, the perceived motion blur can be modeled as the *spatial* response on the retina (i.e. $f_t = 0$), yielding $I_p^f(\vec{f_x})$, as indicated in Eq. 7.

$$I_p^f(\vec{f_x}) = I_c^f(\vec{f_x})A^f(\vec{f_x}, \vec{v}\cdot \vec{f_x}), \tag{7}$$

with $I_p^f(\vec{f_x})$ the perceived spectrum and $I_c^f(\vec{f_x})$ a single image of the video signal $I_c^f(\vec{f_x}, f_t)$.

For LCDs the spatial and temporal component of the aperture is assumed independent, i.e.

$$A(\vec{x}, t) = A_s(\vec{x})A_t(t). \tag{8}$$

Furthermore, by approximating the temporal response of the LCD by a "hold", which is true for infinitely fast responding LC-material, the perceived spectrum on such a display is described by Eq. 9, in case the HVS tracks the motion $\vec{v}$.

$$I_p^f(\vec{f_x}) = I_c^f(\vec{f_x})A_s^f(\vec{f_x})\text{sinc}(\pi T_h \vec{v}\cdot \vec{f_x}), \tag{9}$$

where T_h is the hold-time and $\text{sinc}(\mathbf{x}) = \frac{\sin(\mathbf{x})}{\mathbf{x}}$.

This attenuation is also indicated in Fig. 1 where the spatial dimension is indicated as a 1D signal for clarity reasons. The spatio-temporal normalized frequency spectrum of a static image is depicted in Fig. 1a. The spectrum shears in case of motion (recall Eq. 2) as illustrated in Fig. 1b. Temporal sampling of the motion picture yields repeats of the spectrum, while the spatio-temporal aperture results in an attenuation as indicated for an "ideal hold" LCD in Fig. 1c. The perceived spectrum, in case of eye-tracking by the HVS, is illustrated in Fig. 1d. In this figure, also the limits of the HVS are sketched, assuming TV applications. Comparing Fig. 1a with Fig. 1d shows that the perceived image differs from the original: high spatial frequencies are attenuated, hence motion blur is visible, and repeats are introduced, causing detail flicker.

In the next two sections this analysis is extended for the motion blur reduction methods SFI and MCU.

3. SMOOTH FRAME INSERTION

SFI doubles the frame rate of the video and redistributes spatial frequencies, such that high spatial frequencies are displayed for one of the two sub-frames, while low spatial frequencies are displayed at both sub-frames. Therefore, SFI alternates sharp and blurred images. This is done such that the average of the sub-frame pair is identical to the original frame.

To comprehend that this frequency split reduces motion blur, let us investigate the Fourier transform of the perceived image. Assume $I_c^f(\vec{f_x})$ is split at a spatial frequency f_c into low (LP) and high (HP) spatial frequencies, such that:

$$I_c^f(\vec{f_x}) = I_{\text{LP}}^f(\vec{f_x}) + I_{\text{HP}}^f(\vec{f_x}). \tag{10}$$

SFI alternates a blurred and a sharpened image fast enough to perceive its average. The blurred image equals $I_{\text{LP}}^f(\vec{f_x})$. The sharpened image is chosen such that the perceived average equals $I_c^f(\vec{f_x})$, i.e.:

$$\begin{aligned} I_{\text{blur}}^f(\vec{f_x}) &= I_{\text{LP}}^f(\vec{f_x}), \\ I_c^f(\vec{f_x}) &= \frac{1}{2}\left[I_{\text{blur}}^f(\vec{f_x}) + I_{\text{sharp}}^f(\vec{f_x})\right], \text{ and} \\ I_{\text{sharp}}^f(\vec{f_x}) &= 2I_c^f(\vec{f_x}) - I_{\text{LP}}^f(\vec{f_x}) = I_{\text{LP}}^f(\vec{f_x}) + 2\cdot I_{\text{HP}}^f(\vec{f_x}). \end{aligned} \tag{11}$$

As $I_{\text{HP}}^f(\vec{f_x})$ is displayed only every other sub-frame, its hold-time is halved and the temporal aperture equals

$$A_{t,\text{HP}}^f(f_t) = \frac{1}{2}\text{sinc}\left(\pi\frac{T_h}{2}f_v\right). \tag{12}$$

The temporal aperture for low spatial frequencies and the spatial display apertures are not altered.

Combining the above yields the perceived spectrum when applying SFI, $I_{p,\text{SFI}}^f(\vec{f_x})$, as described by Eq. 13.

$$\begin{aligned} I_{p,\text{SFI}}^f(\vec{f_x}) &= \frac{1}{2}\left[I_{p,\text{blur}}^f(\vec{f_x}) + I_{p,\text{sharp}}^f(\vec{f_x})\right] \\ &= \frac{1}{2}\Big[2\cdot I_{\text{LP}}^f(\vec{f_x})A_s^f(\vec{f_x})A_{t,\text{LP}}^f(\vec{v}\vec{f_x}) + \\ &\qquad 2\cdot I_{\text{HP}}^f(\vec{f_x})A_s^f(\vec{f_x})A_{t,\text{HP}}^f(\vec{v}\vec{f_x})\Big] \\ &= \begin{cases} I_c^f(\vec{f_x})A_s^f(\vec{f_x})\text{sinc}(\pi T_h\vec{v}\vec{f_x}), & |f_x| < f_c \\ I_c^f(\vec{f_x})A_s^f(\vec{f_x})\text{sinc}(\pi\frac{T_h}{2}\vec{v}\vec{f_x}), & |f_x| > f_c \end{cases} \end{aligned} \tag{13}$$

Eq. 13 shows that the attenuation caused by the temporal aperture is reduced for frequencies above the spatial cut-off frequency f_c. Therefore, by choosing f_c sufficiently close to $f_x = 0$, more of the image spectrum profits from a reduced hold time. This is also seen in Fig. 2, where the spatio-temporal frequency spectrum of the perceived image is illustrated for the signal of Fig. 1b after applying SFI, again assuming eye-tracking. It shows that high spatial frequencies are attenuated less compared to Fig. 1d. Fig. 2 also shows that the low spatial frequencies of the first repeats are still significantly reduced, preventing large area flicker. Although choosing f_c too close to zero will increase this flicker.

Sofar, the limited dynamic range for $I_{sharp}(\vec{x}, t)$ has been ignored. In practice, $I_{\text{LP}}(\vec{x}, t) + 2\cdot I_{\text{HP}}(\vec{x}, t)$ requires an extended dynamic range compared to $I_c(\vec{x}, t)$. For the upper extension, this would be physically feasible by reserving headroom, but the lower extension would require negative light intensities. As such, $I_{\text{sharp}}(\vec{x}, t)$ needs to be clipped. This results in a reduced contrast or a limited motion blur reduction. In Section 5, the advantages and disadvantages of SFI will be compared with MCU.

4. MOTION COMPENSATED UP-CONVERSION

In order to reduce motion blur, the hold time must be reduced. This can be achieved by increasing the display rate. However,

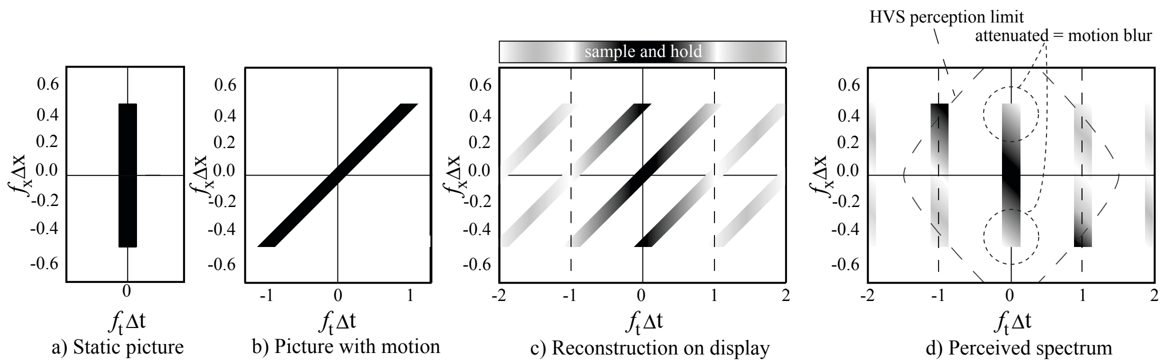

Fig. 1. Spatio-temporal normalized frequency plot (i.e. 1 = sample frequency) of a static picture (a), a moving object (b), reconstruction on an "ideal hold" LCD (c), and the perceived spectrum when motion is tracked (d).

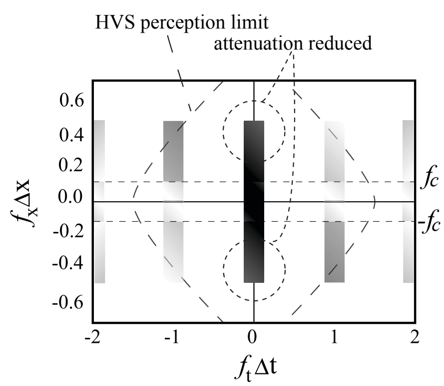

Fig. 2. Spatio-temporal normalized frequency representation of the perceived spectrum of a moving object after applying SFI.

a display rate increase using frame repeat does not result in any motion blur reduction as, for hold-type displays, this does not change the temporal display aperture (recall Eq. 7). Instead, motion compensated interpolation is required, increasing the temporal density of the sampling grid, $\Lambda(\vec{x}, t)$, and changing the temporal aperture.

Similar to Eq. 6, the spatio-temporal spectrum after up-conversion can be obtained as shown in Eq. 14:

$$I'^f_e(\vec{f_x}, f_t) = \left(I'^f_c(\vec{f_x}, f_t) * \Lambda'^f(\vec{f_x}, f_v)\right) A^f_u(\vec{f_x}, f_v) \quad (14)$$

where $I'^f_c(\vec{f_x})$ represents the spatial spectrum of the picture after up-conversion, i.e. a reconstruction of $I^f_c(\vec{f_x})$ at the correct temporal position, $\Lambda'^f(\vec{f_x}, f_v)$ represents the new spatio-temporal sampling grid, and $A^f_u(\vec{f_x}, f_v)$ the display aperture after up-conversion.

Parallel to Eq. 9, the spectrum of the perceived image can be obtained as described by Eq. 15 for an up-conversion factor of u.

$$I^f_{p,\text{MCU}}(\vec{f_x}) = I'^f_c(\vec{f_x}) A^f_s(\vec{f_x}) \text{sinc}\left(\pi \frac{T_h \vec{v}}{u} \vec{f_x}\right) \quad (15)$$

For an up-conversion factor of two, the spatio-temporal frequency spectrum of the signal from Fig. 1b is illustrated in Fig. 3. A similar improvement, compared to SFI, of the high spatial frequency attenuation can be observed. Fig. 3 also shows that, contrary to SFI, the first temporal repeats shift towards higher temporal frequencies, reducing (detail) flicker.

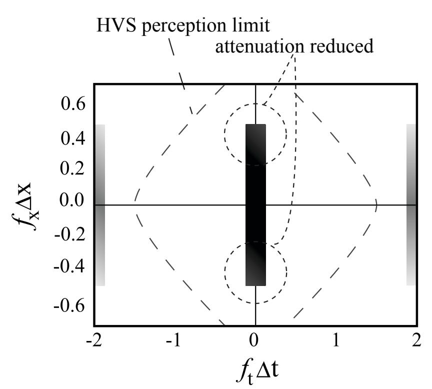

Fig. 3. Spatio-temporal normalized frequency representation of the perceived spectrum of a moving object after MCU with an up-conversion factor of 2.

In practice, motion estimation and the interpolation along the motion trajectory is non-trivial, especially in occlusion areas [11]. An incorrect up-conversion can lead to visible artifacts at occlusion areas, known as "halos". Nevertheless, practical feasibility of MCU has been shown for TV applications [8]. In the next section, the advantages and disadvantages of MCU will be compared with SFI.

5. DISCUSSION

For TV applications many broadcasting standards are in use, either analog, e.g. PAL and NTSC, or digital, e.g. DVB and ATSC, transmitting at a rate of 50Hz or 60Hz. For both transmission rates a further discrimination is made between film and video as their source frame rates differ. The 50Hz standards use a source frame rate for film of 25Hz and 50Hz for video, while the 60Hz standards have source frame rates of 24Hz and 60Hz, respectively. For the comparison between the motion blur reduction of SFI and MCU, correct detection of the source frame rate and correct deinterlacing [8] is assumed.

SFI can not be applied to film at the film source rate (i.e. 24Hz or 25Hz), as the assumption of Eq. 11 does not hold and flicker would be observed. Also, in case a frame repeat is applied to increase the display rate of film, SFI is not suitable, as it enhances the visibility of motion judder, caused by the low intrinsic frame rate. Only after applying MCU to increase the source frame rate above the judder limit, SFI can be applied to reduce motion blur [9]. As such, for LCD-TVs that feature motion blur reduction, MCU is a mandatory processing block, even when MCU is not used to reduce motion blur. In case of video, SFI can be applied directly, yielding a frame rate of 100Hz or 120Hz, respectively.

Motion blur reduction with MCU allows for arbitrary output frame rates. However, as integer factors are preferable for implementation efficiency reasons, an up-conversion factor of two is assumed in case of video, and four (25Hz) or five (24Hz) is used in case of film, resulting also in 100Hz or 120Hz display frame rates, respectively.

As already indicated in the previous sections, SFI and MCU can cause visible artifacts. SFI results in a reduced contrast or limited motion blur reduction whenever the limits of the dynamic range are exceeded. MCU can produce halo-artifacts when motion is estimated incorrectly at object boundaries. The limitation of SFI is fundamental, as negative light intensities can not physically be displayed, while the artifacts produced by MCU are not fundamental, as they are a result of practical limits on the available compute power.

For TV applications, the computational complexity and required resources are important. To implement SFI, a spatial filter to split low and high spatial frequencies is necessary, combined with additional logic to limit and compensate the video signal in case it extends the dynamic range. As such the complexity of SFI is low. MCU requires the estimation of the true motion in video, combined with an interpolation along the motion and, therefore, has a high complexity. However, as MCU is required for TV applications that feature motion blur reduction, a fair cost comparison between SFI and MCU should only take the additional complexity of the *higher* frame rate conversion factor into account. This makes the cost difference less obvious and therefore dependent on the actual implementation.

6. CONCLUSIONS

Motion blur on LCDs has been analyzed by examining the spatio-temporal spectrum of the perceived image, taking eye-tracking of motion into account. This analysis has been extended to examine the performance of the motion blur reduction techniques SFI and MCU.

The applicability of SFI and MCU for TV applications has been discussed. It was found that SFI has a limited applicability for TV applications, as it is not directly suitable for film content and has fundamental limitations for high contrast details. MCU is required for LCD-TVs that feature motion blur reduction and, as such, the (cost) benefit of using SFI for motion blur reduction should be compared with the added costs of applying MCU at a higher up-conversion factor.

7. REFERENCES

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