41.2: Judder-Induced Edge Flicker in Moving Objects

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Abstract
The threshold motion rates that produce edge flicker were determined as a function of contrast, luminance and sampling frequency. A passive filtering scheme, called the Movieola filter, appears to mitigate this artifact. The Movieola filter produces interpolated frames based on a passive two-tap discrete dissolve. It is simple to implement and therefore relatively inexpensive to manufacture.

Introduction

Reconstructing a moving image on a display involves two sampling steps. First the motion must be captured by periodically sampling the image in time. Then the sampled motion must be reconstructed on a display.

Natural images are commonly captured by scanning image locations with a raster, or by sweeping locations one row at a time, or, as in film, by simultaneously sampling every location. When every location within a time period has been sampled, the process is repeated and new data are gathered at each location for the next time period. This process is repeated at a temporal frequency f and period $1/f$, defined by the sampling period and any associated overhead. In film capture the frequency can vary and will not be the same as the frequency used to reconstruct. All three methods sample discretely in time, and produce slightly different samples depending upon f, the sampling method and the distribution of $1/f$ between sampling and overhead. Generally f is 24 Hz or greater.

The sampling duty cycle, $0 < \alpha \leq 1$ defines a sampling period, $\alpha(1/f)$ sec. Sampling has a fixed temporal overhead that is required to move film or to read out samples and reset counters. Typically α is 1/2 and this produces motion blur when objects move during the sampling period. Discrete temporal sampling and the sampling duty cycle together produce detectable artifacts for moving images. These include motion blur, image breakup and judder[1].

The visibility of motion artifacts depends upon the rate of motion in the images, the sampling frequency and method. Commercial video and cinema limit camera pan and zoom rates and the velocity of moving objects to reduce the salience of these artifacts (1).

Unique display characteristics can generate additional noticeable artifacts when the image signal is reconstructed on a display. For example, CRTs flicker when refreshed at 30 Hz because of the rapid decay of phosphor light emission following excitation. Television interlace hides this flicker signal by refreshing the screen at 60 Hz and presenting half the image on each refresh. As screen brightness increases the required refresh rates for CRT displays increase to hide the flicker signal (2). Cinema projectors hide the flicker signal produced by the shutter dark period by double shuttering each frame of film at 48 Hz and limiting peak brightness to less than 12 ftL.

TFT-LCD displays do not produce a traditional flicker signal because the light valve is latched to a set intensity level. Liquid crystal light valves can produce flicker due to the slow and asymmetric nature of the LC optical switch, the need to periodically reverse the polarity of the addressing field to prevent image sticking, or the dissipation of holding charge at each pixel location. Because this signal is lower in contrast than the flicker signal produced by a CRT or film projection, it is harder to see.

Double shuttering in cinema projection interpolates an additional frame during image reconstruction. There is no reason other than complexity and cost to prevent signal processing from producing an interpolated frame that is different from the sampled frame. One signal processing method uses nonlinear filtering to interpolate motion components within the scene along the directions of the motions to produce an interpolated inter-frame (3). These methods, though complex and costly in terms of processing load, save signal bandwidth. Interpolation along motion directions has been used to reduce judder.

When a human watches a moving image, the eye tends to follow the motion with smooth pursuit eye movements. These have the effect of slowing or even stabilizing the moving image on the observer's retina. An additional artifact, edge flicker, that we believe is related to judder is produced by the conjunction of smooth pursuit eye movements and motion sampling. This is the subject of this report.

In natural scenes, smooth pursuit stabilizes or reduces the temporal rate of motion of a moving image on the retina. Smooth pursuit of a sequence of momentarily stationary

[1] When smooth real motion appears jerky in a reconstructed image sequence this is called motion judder.

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images, however, produces a geometric shearing of the image on the retina (4).

A horizontal line segment moving from left to right across a screen can be described in a space-time diagram as in Fig. 1 panel a. The abscissa represents the location of the line in space and the ordinate represents time. A continuous motion from the left to the right is represented by the gray tilted column in panel a. The line bisecting the column is the locus of foveal fixation for a synchronous smooth eye motion pursuing the moving line. Panel b in this figure represents the motion in retinal coordinates as opposed to the world coordinates shown in panel a. Here the smooth pursuit eye movements have stabilized the image on the retina.

Panel c in Fig. 1 shows the sampled and reconstructed image on an ideal latched pixel display. On this display the sample frames are instantaneously updated to the next frame. The stair step appearance of the reconstructed signal graphically illustrates the judder signal or jumping that occurs between frames of the reconstructed signal in world coordinates. The stair steps are the temporal analog to the discrete sampling artifact known as jaggies. Motion blur in panel c is depicted as a lengthening of the line segment in the reconstructed signal. The locus of foveal fixation is shown as the bisecting line in panel c. Panel d shows the space-time diagram for this motion in retinal coordinates. The image shear in the retinal image produced by the brief static periods in world coordinates produces a flicker signal at each end of the line segment. Eye movements and discrete sampling generate this signal. It appears as edge flicker.

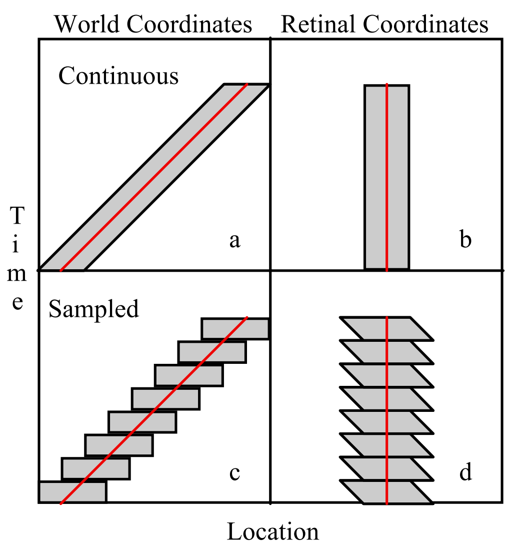

Figure 1. Space-Time diagrams for a moving line segment.

In this report we have measured the motion rates at which this edge flicker signal exceeds a perceptual threshold. Additionally, we have documented that a passive filtering scheme that we call the Movieola or fade filter can mitigate this artifact. The Movieola filter is a passive filter; it produces interpolated frames with a passive two-tap filter that is simple to implement and therefore relatively inexpensive to manufacture. In this report we empirically determine the motion rates that produce edge flicker as a function of contrast, luminance, and sampling frequency.

Methods

Discretely sampled motion sequences of horizontally moving vertical bars or of a single bar were created for an ideal camera with a linear integrator sensor. The shutter duration was half the sampling period, $\alpha(1/f)$, where α=0.5. A series of motion samples was created with motion rates from 5 pixels per second to 2000 pixels per second. The viewing distance to the screen was set so that 100 pixels per sec corresponded to a motion rate of 1.82° per second visual angle. At this viewing distance, the width of the vertical bars was 0.18° visual angle.

The motion sequences were generated for sampling frequencies of 15, 20, 25, 30 Hz. The display on which the sequences were reconstructed was either a CRT or a TFT-LCD. The motion sequences were reconstructed at the same frame rate at which they were sampled. On the CRT the sampled motion frames were repeated to achieve the desired frequency. For example, each 20 Hz sample frame was presented 3 times to achieve the 20 Hz sampling frequency on the CRT which was refreshed at 60 Hz. The CRT effectively double-, triple- or quadruple-shuttered each sample frame to produce the required sampling and reconstruction. The sampled frames on the TFT-LCD were reconstructed essentially continuously for 1/15th, 1/20th, 1/25th or 1/30th of a second due to the latching characteristic of LC pixels.

The bar(s) threshold velocity in pixels per second was determined for five different brightness levels, 34, 17, 8.5, 4.3, 2.1 ftL respectively, and five different nominal Michaelson[2] contrasts, 100, 75, 50, 25, & 5% respectively.

Results: Threshold Motion for Edge Flicker

Figure 2 shows thresholds for edge flicker across frame rates for three of the five levels of brightness and two of the five levels of contrast studied, for observer JW. The curves show the concave-upward shape that was typical for all conditions and all observers.

[2] Michaelson contrast = $(L_{max}-L_{min})/(L_{max}+L_{min})$.

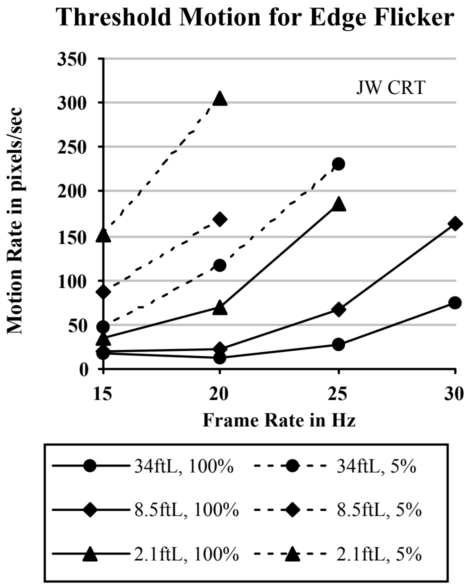

Fig. 2 The results for observer JW for motions viewed on a CRT. Three brightness levels and two contrast conditions are shown. Each curve is labeled by the brightness in ftL and the nominal Michaelson contrast.

The separation by brightness, where increased brightness resulted in increased edge flicker and thus a lowering of threshold motion rates, was a robust and consistent feature for all conditions and observers. When contrast was lowered to 75% or 50%, the results were not significantly different from the 100% contrast condition. However, the 5% contrast condition resulted in the kinds of differences shown, and the 25% contrast condition fell between 5% and 100% in a clear and consistent manner.

Comparing CRTs and LCDs

When the results for CRTs vs. LCDs were compared for both observers and in all conditions, no consistent differences were found.

Comparing a Two-Tap Discrete Movieola Filter to Up-Sampling by Replication

Fig. 3 shows the results for one subject of a comparison of a two-tap discrete fade or dissolve filter to simple up-sampling by replication. We have chosen to call this filter a Movieola filter after the film-editing tool, the Movieola™, which performs this filtering operation in the analog domain. A Movieola combines two successive frames of a film by imaging them through a rotating prism optical combiner. This device performs an analog convex sum operation also called a fade or dissolve of one frame into the other.

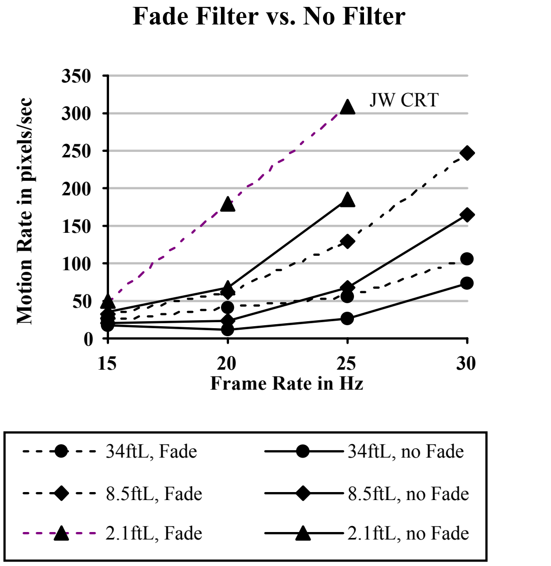

Figure 3. A comparison of simple up-sampling by replication of sampled image frames to a two-tap discrete dissolve filter, called a Movieola Filter.

Our methodology for reconstructing the signal at various sample frequencies did not allow us to independently control the number of up-sampled images between sampled data frames. At 30 Hz there was one up-sampled interpolated frame, at 25 and 20 Hz there were two up-sampled interpolated frames, and at 15 Hz there were three up-sampled interpolated frames. Despite this limitation, it is clear from the data in Fig. 3 that this filtering operation mitigates edge flicker.

Conclusions

Luminance appears to be the dominant controlling independent variable second only to frame rate in producing this artifact. As the luminance of the screen increases, edge flicker becomes apparent at even slow motion rates. This observation is similar to the requirement that cinema projection not exceed 8 to 12 ftL peak white.

Contrast plays an important role in this artifact but as in all contrast phenomena its impact is most apparent near threshold. In these data contrasts above 25% produced similar bar velocity thresholds. The bar targets were effectively low spatial frequency targets with a fundamental around 2.75 cycles per degree. The impact of contrast would be expected to be greater at higher spatial frequencies, but this condition was not tested.

The data collected on the CRT were produced by up-sampling similar to cinema projection. The CRT frame rate was 60 or 75 Hz (depending upon the sampling frequencies, 75 Hz for the 25 Hz condition and 60 Hz for all other conditions). The TFT-LCD refresh rates were the same as the sampling rates. The sampling period for image capture was 50% for both presentations. The reconstruction-sampling period was nominally 6% for the CRT due to the rapid phosphor decay of light emission and 100% for the TFT-LCD. Differences in individual results between CRT and LCD presentations were small and not systematic.

The dominant finding is that the judder edge flicker signal has impact at most frequencies regardless of whether or not the signal is on a higher frequency carrier as it is in cinema and television. Another implication of these results comes from the comparison of the fade or Movieola filter to the no filter or repeated frame up sampling condition. The data in Fig. 3 show an advantage with respect to artifact mitigation by employing a passive discrete two tap dissolve.

The dissolve or fade filter is a simple signal processing operation that requires one buffered image in addition to the current image and convex sum operations on pixels. Motion compensation using dynamic filters requires more processing and switching power to do the required computations to estimate the motion directions. The advantage of motion compensation over fade filtering has not be thoroughly explored or quantified in these data.

Questions that remain to be quantified and investigated include the advantage of higher sampling rates to fade filters and the value of additional interpolated sub-frames for mitigating edge flicker artifacts. The effect of three-two pull down to convert film formats to NTSC on edge flicker is also an open question.

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