Comparison of Two Frame Rate Conversion Schemes for Reducing LCD Motion Blurs

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***Abstract*—Liquid crystal display (LCD) is known to have motion blur due to the slow response and sample-hold characteristics of the liquid crystal (LC). To alleviate the LCD motion blur, improving the LC response is the most fundamental solution. However, if the response time is shortened, then more frames are needed and hence frame rate up conversion (FRUC) should be used. In this paper, we study two FRUC methods. We compare the output signal qualities by studying the temporal and spatial profile of the two methods. We use the solution of Erickson-Leslie equation to derive the step response, in contrast to the existing literature where the resistor-capacitor (RC) approximation and uniform averaging function are used. The step response we derived is able to model not only the general trend of the rising and falling edges, but also the effects of different gray level transitions. Based on the step response, we analyze the two methods by comparing the observed signal in both the spatial and temporal domain.**

***Index Terms*—Frame rate up conversion, liquid crystal displays, motion blur.**

I. Introduction

LIQUID crystal display (LCD) is known to have motion blur due to the slow response and sample-hold characteristics of the liquid crystal (LC). Thus, in order to reduce the motion blur, one can make the LC responds faster and increase the frame rate. In this paper, we compare the two most popular frame rate up conversion (FRUC) methods used in today's LCD TV.

The first method uses motion compensation to fully interpolate the missing frames [1]. In this method, a low frame rate video is upsampled to a high frame rate video by inserting additional frames between every two consecutive frames. This method is costly, but the temporal resolution is doubled (Fig. 1).

The second method does not interpolate the missing frames. However, each frame is partitioned into three horizontal bands and displayed alternatively. As shown in Fig. 1, we display sequentially the top and bottom bands of frame 1, middle band of frame 1, top and bottom bands of frame 2, middle band of frame 2, and so on. This method is less expensive, but intuitively it degrades the picture quality.

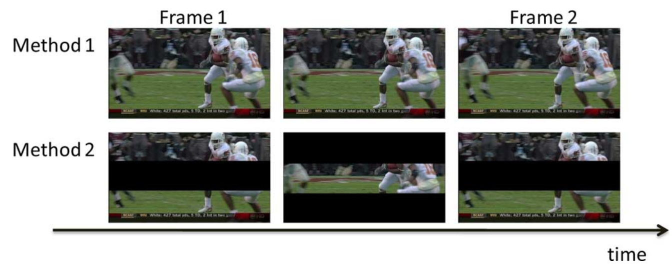

Fig. 1. Two frame rate up conversion schemes. Top: Full frame insertion by motion compensation (MC); bottom: black data insertion method.

The objective of this paper is to explore two fundamental questions. First, in order to analyze the motion blur effect of these two methods, an accurate LCD impulse response and step response is required. In literature, the step response of an LCD is frequently modeled as a uniform averaging function [2] or a resistor-capacitor (RC) type of functions [3]. However, as we will discuss in Section II that these models are insufficient to characterize some important features of an LC.

The second objective of this paper is to analyze the two above mentioned FRUC methods. Our goal is to compare the observed signal in both the temporal and spatial domain.

The findings presented in this paper are independent of human visual system (HVS) because HVS only affects the human perception of the image, but does not affect the physical mechanism of the LC and FRUC presented in this paper. Also, the analysis presented in this paper is independent of the frame rate. The results are valid for 60 Hz, 120 Hz, and 240 Hz systems.

II. LCD Impulse Response

To determine the step response of an LC, we solve the Erickson–Leslie equation:

$$\begin{aligned}&\left(K_{11}\cos^2\phi + K_{33}\sin^2\phi\right)\frac{\partial^2\phi}{\partial z^2}\\ &+(K_{33}-K_{11})\sin\phi\cos\phi\left(\frac{\partial\phi}{\partial z}\right)^2\\ &+\epsilon\Delta\epsilon E^2\sin\phi\cos\phi = \gamma_1\frac{\partial\phi}{\partial t}.\end{aligned}$$

Under certain conditions[1], it can be shown that the step response to a boxcar signal is given by

[1]These conditions include small angle approximation ($\sin\phi \approx \phi$ and $K_{33} \approx K_{11}$) and zero pretilt angle at surface boundaries, see [4] for details.

Manuscript received May 04, 2010; revised June 16, 2010; accepted June 16, 2010. Date of publication June 28, 2010; date of current version July 06, 2010. This work was supported by Croucher Foundation scholarship and Samsung Information Systems America (SISA). Supplementary materials can be found at http://videoprocessing.ucsd.edu. The associate editor coordinating the review of this manuscript and approving it for publication was H. Vicky Zhao.

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Digital Object Identifier 10.1109/LSP.2010.2055238

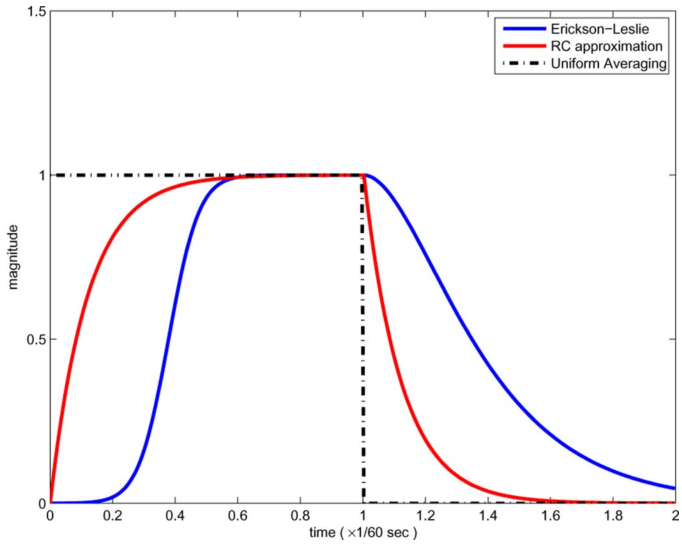


Fig. 2. Step responses of our model (Erickson–Lesie), the resistor-capacitor (RC) approximation [3] and ideal low pass [2].

$$I_F(t) = \sin^2\left(\frac{\delta_0 \exp\left(-\frac{2t}{\tau_f}\right)}{2}\right) \tag{1}$$

for the falling edge, and

$$I_R(t) = \sin^2\left(\frac{\frac{\delta_0}{2}}{1+\left[\frac{\phi_\infty^2}{\phi_0^2}-1\right]\exp\left(-\frac{2t}{\tau_r}\right)}\right) \tag{2}$$

for the rising edge. The details of these equations can be found in [4].

The impulse response of the liquid crystal is the derivative of the step response. Taking the derivatives of the functions in (1) and (2) yields

$$h_F(t) = \frac{\delta_0}{\tau_f}\sin\left(\delta_0 e^{-2t/\tau_f}\right)e^{-2t/\tau_f}, \quad t \geq T \tag{3}$$

$$h_R(t) = \sin\left(\frac{\delta_0}{1+\left[\frac{\phi_\infty^2}{\phi_0^2}-1\right]e^{-2t/\tau_r}}\right) \times \left[\frac{\delta_0}{\tau_r}\left[\frac{\phi_\infty^2}{\phi_0^2}-1\right]e^{-2t/\tau_r}\right], \; 0 \leq t \leq T \tag{4}$$

where T is sampling period (16.67 ms for 60 Hz system).

Fig. 2 shows the step response of our model (Erickson-Leslie). In this figure, we let $\phi_\infty = 85$, $\phi_0 = 5$, $\delta_0 = \pi$, $\tau_r = 2.5$ ms, and $\tau_f = 16.67$ ms. These numbers can be justified, for example τ_f is estimated by considering a commercial Merck negative nematic MLC-6608 mixture. The parameters of MLC-6608 are: rotational viscosity $\gamma_1 = 186$ mPas at 20°C, bend elastic constant $K_{33} = 18.1 \times 10^{-12}$ N, cell gap $d = 4.6$ μm. Put these values into the definition of $\tau_f := \gamma_1 d^2/K_{33}\pi^2$, we have $\tau_f = 22.03$ ms. For thinner cell gap where $d = 4$ μm, we have $\tau_f = 16.67$ ms.

In Fig. 2, we also show the step responses of the resistor-capacitor (RC) approximation [3] with $\tau = 2$ ms and $T = 16.67$ ms, and that of the uniform averaging function [2]:

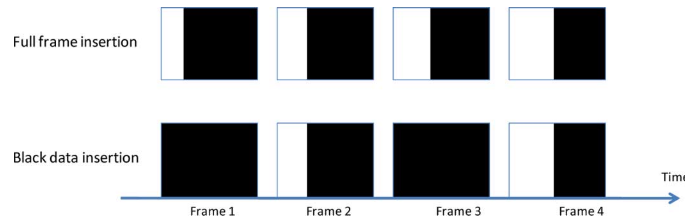


Fig. 3. Analysis setup. We consider a black and a white half plane moving horizontally.

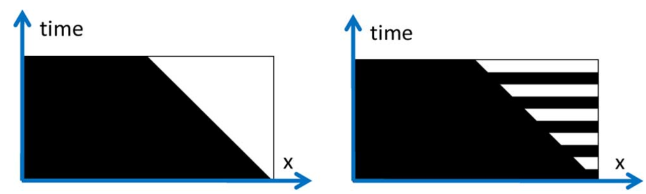


Fig. 4. Space–time plots of (left) full frame insertion method and (rright) black data insertion method.

$$I_{RC}(t) = \begin{cases} e^{-(t-T)/\tau}, & t \geq T \\ 1-e^{-t/\tau}, & 0 \leq t \leq T, \end{cases} \quad \text{and}$$

$$I_{avg}(t) = \begin{cases} 0, & t \geq T \\ 1, & 0 \leq t \leq T. \end{cases}$$

There are some significant differences between the three models as shown in Fig. 2. First, the RC approximation and the uniform averaging function have equal fall and rise time. However, as mentioned in [5], an LC cell takes less time to orientate itself in the presence of electric field (rise time) and it takes more time to return to its original state (fall time)[2]. This phenomenon is characterized by our model, but not the other two. Second, the RC approximation and the uniform averaging functions assume that the LC starts to transmit light immediately when it receives a signal. However, Nei *et al.* [6] showed that there is a latency before the LCD starts to transmit light, which is caused by the pre-tilt angle. As shown in Fig. 2, our model is able to characterize this latency, but the other two models fail. Therefore, even though the RC approximation and uniform averaging functions show some general trends, they cannot model the underlying characteristics of the LC.

III. Analysis

A. Setup

We now use the step response described above to analyze the performance of the full frame insertion method and black data insertion method. To start with, we consider a black and a white half plane moving horizontally with a constant speed. The images in Fig. 3 illustrate the idea. Here only the top 1/3 band of the frames are shown because the other 2/3 band can be analyzed similarly.

Since all pixels along the y-axis of an image shown in Fig. 3 are identical, a convenient way to analyze the image sequence is to consider a space-time plot as shown in Fig. 4. The space-time plot consists of the displacement (horizontal axis) and the time (vertical axis). A pixel at a position x of the tth image has a value located at the (x, t)th coordinate in the space-time plot.

[2]Assume that the gray level transition is from 0 to 255.

Fig. 5. Results of convolving the space-time plots with the transfer function defined in Section II. (Left) Full frame insertion and (right) black data insertion.

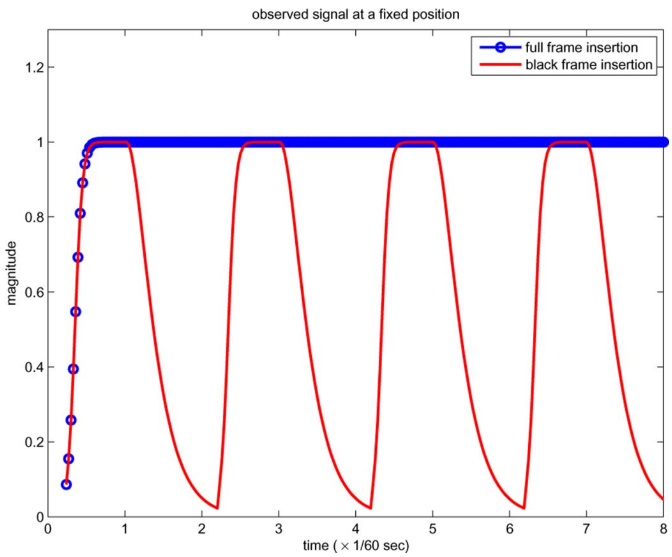


Fig. 6. Observed signal at a fixed position $x = 1320$. The full frame insertion method gives a steady temporal response whereas the black data insertion method gives an oscillatory temporal response.

Fig. 7. A video sequence, with frame rate doubled by [top] full frame insertion, [bottom] black data insertion.

Our goal is to calculate the observed signal. From [2, eq. (7)], the observed signal is given by

$$I_o(x,y,t) = \int_0^\infty h(\tau) I_c(x - v_x\tau, y - v_y\tau, \tau) d\tau \qquad (5)$$

where $I_c(x,y,t)$ is the input signal, $h(t)$ is the impulse response and $I_o(x,y,t)$ is the observed signal. Equation (5) is essentially a convolution in time. In our problem, the impulse response is given by (3) and (4), and the input signal is the space-time plot as shown in Fig. 4. Using the same parameters discussed in Section II, the observed signal of the LC using the two methods are shown in Fig. 5.

B. Temporal Comparisons

The temporal responses of the two methods can be obtained by considering the intensity change at a particular pixel location. In the space-time plot, we make a vertical cross section at a pixel located at the right end and show the intensities in Fig. 6. At this particular pixel location, the full frame insertion method gives a rising edge at the beginning, and maintains at a constant level afterwards. Therefore, as long as temporal response is concerned, we conclude that full frame insertion method gives a steady temporal response. The initial rising edge can be interpreted as the transient of the LC when the LCD is being powered on. Once the LCD is powered on, the pixel stays constant.

In contrast, the black data insertion method shows fluctuations of intensity in time. This phenomenon is caused by the inserted black frames, because the LC transmittance is forced to drop to zero during the black frames. Due to the intensity fluctuation, a video displayed using black data insertion method will have blinking artifacts.

To see that, we generate a few video sequences, as shown in Fig. 8. These video sequences are available on http://videoprocessing.ucsd.edu/~stanleychan. For each video sequence, we increase the frame rate by full frame interpolation method (as shown in Fig. 7 [top]), and black data insertion method (as shown in Fig. 7 [bottom]). The original video sequence is played at 30 fps, and the interpolated sequence is played at 60 fps. As one can view using a regular 60 Hz LCD TV, the intensity fluctuation of the black-data insertion method is present, and can be seen easily.

C. Spatial Comparisons

We now compare the two methods in spatial domain by considering the blur widths.

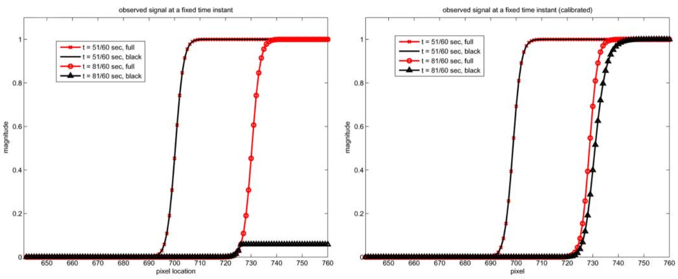
Blur width is defined to be the spatial displacement for a transition to rise from 10% to 90% of peak intensity, or fall from 90% to 10% of peak intensity. For the full frame insertion method, blur width is constant at any time instants. For example, the red curves in Fig. 9(a) are identical at $t = 51/60$ s and $t = 81/60$ s. However, for the black data insertion method, the maximum intensity is changing in time. For example in Fig. 9(a), the black colored curve of $t = 51/60$ s peaks at a different level as that of $t = 81/60$ s.

The blur width of the black data insertion method cannot be calculated simply by taking the 10% and 90% magnitude of the curves in Fig. 9(a) because the final and initial gray levels are changing in time. Therefore, we have to resolve this issue before comparing the blur widths.

Using (1) and (2), the effect of gray level change can be modeled by the net phase change angle δ_0. If the gray level transition is large, then net phase change angle will also be large. The effect of the net phase change angle is that it affects the maximum magnitude and the transient characteristics of the step response. Fig. 10(a) shows the step responses of the LC with different δ_0. For better comparisons, the normalized step response is plotted in Fig. 10(b). As seen, if δ_0 is large (hence gray level transition is large), the rising edge is also steep.

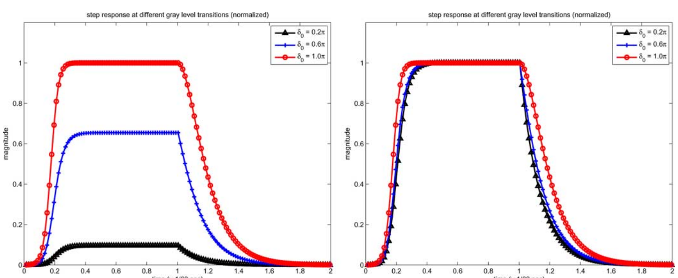
Since gray level transitions affect the rising and falling edges of the step response, we need to compensate the curves in Fig. 9(a) before comparing the blur widths. To do so, we first uniformly quantize the gray levels into eight scales. For the kth scale ($k = 1, \ldots, 8$), we let $\delta_0 = k\pi/8$, and substitute δ_0 into the impulse response ((3) and (4)). The calibrated signal is then the convolution between the input signal and the impulse

Fig. 8. Four video sequences comparing full frame insertion and black data insertion.



(a) (b)

Fig. 9. (a) Observed signal at fixed time instants $t = 51/60$ s and $t = 81/60$ s. Note that the observed signal of black data insertion method is changing at different time instants. (b) Calibrated signal of (a).



(a) (b)

Fig. 10. (a) Step response of a liquid crystal at different gray level transitions. (b) We normalize the curves of (a) so that the maximum is 1.

response with $\delta_0 = k\pi/8$. Fig. 9(b) shows the observed signals after calibration.

IV. Discussions

We now discuss a few issues regarding the analysis above.

First, in terms of temporal comparisons, we conclude that full frame insertion method is better because the intensity level is changing smoothly. The black data insertion causes fluctuation of intensity in time, and hence flickering. At low frame rate, the difference between the two methods is obvious. Experiments in Section III-B verifies this conclusion. At high frame rate, black data insertion still causes intensity fluctuation. However, it may become less apparent to our eyes due to the lowpass characteristics of the human visual system (HVS). The masking effect of the HVS is an interesting phenomenon, and we will consider it in our future research topic.

Second, in terms of spatial comparisons, we conclude that neither method is better than the other. As shown in Fig. 9(b), the rising edge blur width of the full frame insertion method is shorter than that of the black data insertion method. However, though not shown in Fig. 9(b), we can conclude from Fig. 10(b) that the falling edge blur width of the full frame insertion method is longer than that of the black data insertion method. This implies that full frame insertion method has shorter blur width for rising edge whereas black data insertion has shorter blur width for falling edge.

An important observation is that the spatial blur width of the black data insertion method is time dependent. Consequently, the conventional blur edge width (BEW) is not suitable for measuring the spatial blur width. A BEW is determined either by a camera or simulated based on the convolution between the temporal profile and a rectangular pulse [7]. BEW is a good metric for a number of LCD systems, including the back-light flashing systems because the duty cycle of the back-light is usually a multiple of the display refresh frequency, and hence the rectangular pulse in [7, eq. (1.9)] is several times as wide as the signal pulses. However, BEW does not work for black data insertion because black data insertion is a special case of back light flashing where the flashing duty cycle and the display refresh frequency are identical. In this case, the spatial profile (i.e., the convolution output in [7, eq. (1.9)] will be fluctuating, and hence there is no clear 10% and 90% intensities.

V. Conclusion

We first analyze the transfer function of the liquid crystal display (LCD). The transfer function is derived from Erickson–Leslie equation, which exhibits significant difference compared to the resistor-capacitor (RC) type of functions, and the uniform averaging function. The new model is able to characterize not only picture motion, refresh rate and liquid crystal property, but also the applied voltage, net phase change angle and the gray level transition.

We also compare the performance of two commonly used frame rate up conversion method: full frame insertion method and black data insertion method. In the time domain, we find that full frame insertion method gives more stable temporal response than black data insertion method. In the spatial domain, we find that neither one is better than the other. We also observe that the conventional blur edge width (BEW) is not suitable to measure the performance of black data insertion method.

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