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The compatibility of LCD TVs with time-sequential stereoscopic 3D visualization

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ABSTRACT

Liquid Crystal Displays (LCD) are now a popular display technology for consumer television applications. Our previous research has shown that conventional LCD computer monitors are not well suited to time-sequential stereoscopic visualization due to the scanning image update method, the hold-type operation of LCDs, and in some cases slow pixel response rate. Recently some new technologies are being used in LCD TVs to improve 2D motion reproduction - such as black frame insertion and 100/120Hz capability. This paper reports on the testing of a selection of recent LCD TVs to investigate their compatibility with the time-sequential stereoscopic display method – particularly investigating new display technologies. Aspects considered in this investigation include image update method, pixel response rate, maximum input frame rate, backlight operation, frame rate up-conversion technique, synchronization, etc. A more advanced Matlab program was also developed as part of this study to simulate and characterize 3D compatibility and calculate the crosstalk present on each display. The results of the project show that black frame insertion does improve 3D compatibility of LCDs but not to a sufficient level to produce good 3D results. Unfortunately 100/120Hz operation of the tested LCD did not improve 3D compatibility compared to the LCD monitors tested previously.

Keywords: Stereoscopic, time-sequential 3D, LCD, compatibility, 100Hz, 120Hz, black frame insertion.

1. INTRODUCTION

The time-sequential (also known as: field-sequential, frame-sequential, time-multiplexed, alternate field) stereoscopic display technique has a long and successful history of use with CRT (Cathode Ray Tube) displays. High-quality full-color flicker-free stereoscopic images can be seen with the aid of Liquid Crystal Shutter (LCS) 3D glasses when operating at a display frequency of 120Hz. CRTs have now almost completely been replaced by LCDs (and Plasma) displays in the home television market, so naturally people are interested to know whether LCD TVs can be used with LCS 3D glasses to view stereoscopic 3D content. Our previous work has shown that conventional consumer LCD computer monitors [1] and Plasma displays [2] are not well suited to time-sequential stereoscopic 3D visualization. Some of the incompatibility reasons cited were fundamental to the way that the displays output light and generated images, but other factors were more specific to way that the specific display was implemented (usually related to video processing).

For the purposes of this discussion, we divide LCD TVs into three categories: (1) Commercially released displays in which the 3D compatibility of the display is unstated, (2) commercially released displays which are stated as being 3D Ready or Stereoscopic 3D capable, and (3) customized displays which are being developed in R&D labs but are not commercially released. This paper aims to establish whether any LCDs in Category 1 can be used for time-sequential 3D visualization. Obviously the 3D status of displays in Category 2 is already known. It is hoped that the analyses and results of this paper will be helpful for the innovations taking place in Category 3, but since such displays are not currently commercially available, it is outside the scope of this paper.

2. NEW LCD TECHNOLOGIES

Since the publication of our LCD compatibility paper [1] in 2006, a number of new technologies have been introduced into some commercially released LCD TVs. These new technologies are: Black Frame Insertion (BFI), 120Hz refresh,

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and modulated backlight. These technologies have been introduced to improve the reproduction of moving images in 2D viewing (nothing to do with 3D viewing). Conventional LCDs suffer from a problem called image smear (often known as motion blur) which is caused by LCDs being a hold-type display [3]. These new technologies reduce the presence of image smear, but this paper considers how these technologies affect time-sequential 3D compatibility.

2.1 Black Frame Insertion (BFI)

Black Frame Insertion can be considered two ways, either (a) the display time of each individual frame is reduced and replaced with black, in effect reducing the duty cycle of each frame, or (b) the display adds a black frame between each original video input frame. Image smear will be reduced because the hold-time is reduced, however one problem with this technique is that if the backlight brightness isn't increased, the brightness of the display will be reduced in proportion to the amount of BFI introduced. It could be argued that the insertion of the intermediate black frames increases the display frequency up to 120Hz, but these extra frames are just black, not new image frames, so it is still 60 frames per second, but with a reduced on time per frame. BFI is sometimes compared to the modulated backlight technology, and although the effect on image smear is similar, BFI is different because it is implemented at the LCD panel, not the backlight.

2.2 120Hz Refresh

This technology works by interpolating extra frames between the original 60Hz frames provided at the video signal input. The 60 original frames per second plus the new interpolated frames interspersed between the original frames results in 120 frames per second (120Hz). At the new 120Hz image rate, the time on screen per frame is halved, and hence the integration time is halved which in turn reduces image smear for moving objects. With 60Hz input sources the display rate is doubled to 120Hz, and for 50Hz input sources the display rate is doubled to 100Hz.

2.3 Modulated Backlight

Also known as strobing backlight or scanning backlight, in this case image smear is reduced because the on-time of each frame is reduced by switching the backlight on and off (reducing the duty cycle). With a strobing backlight the entire backlight is turned on and off all at once. With a scanning backlight the on and off cycle is scanned down the display in segments, usually following the scan-like image update of the LCD.

3. IMPORTANT LCD AND LCS PROPERTIES

Our work in 2006 [1] identified several important properties of LCD monitors and LCS 3D glasses which determine the compatibility of a particular display with the time-sequential stereoscopic 3D display method.

3.1 LCD and LCS Native Polarization

The LCD and the LCS both have a native (linear) polarization angle – if these are orthogonal, the display will appear black when viewed through the LCS glasses. This is easily overcome by the use of a quarter or half-wave retarder, or designing the LCS with a different polarization orientation.

3.2 Refresh Rate

The maximum refresh rate of a monitor determines the maximum speed at which it can display a sequence of images. A refresh rate of 100-120Hz is usually considered necessary for flicker-free viewing with the time-sequential 3D method. The maximum refresh rate which can be used successfully for time-sequential 3D is determined by two factors: (a) the maximum rate at which the input electronic will accept a video signal, and (b) the maximum rate at which the internal display electronics will drive the LCD panel. Generally, the lower of these two maximums will be the important number for 3D purposes.

3.3 LCD Pixel Response Time

It takes a finite period of time for an individual pixel to be switched from one state to another. For time-sequential 3D viewing, the LCS should not be opened until the switching of the pixel (from one state to another) has stabilized sufficiently. If the pixel response time is too slow, the image would never stabilize before the next image was displayed, and hence could not be used for time-sequential 3D viewing.

3.4 Image Update Method

A new image is written to an LCD one line at a time from the top of the screen to the bottom. This transition from one image to the next is similar to the way that an image is scanned on a CRT, except that an LCD is a hold-type display whereas a CRT is an impulse-type display [3]. The scan-line image update method of a conventional LCD is illustrated in Figure 1. It is evident from this figure that there is no one time when a single image is shown exclusively on the whole LCD panel – this is particularly so for LCD monitors with a long pixel response rate, but is also true for LCDs with a short pixel response rate. In this example there is no single time when the shutters in the LCS glasses could open and see exclusively a single perspective image.

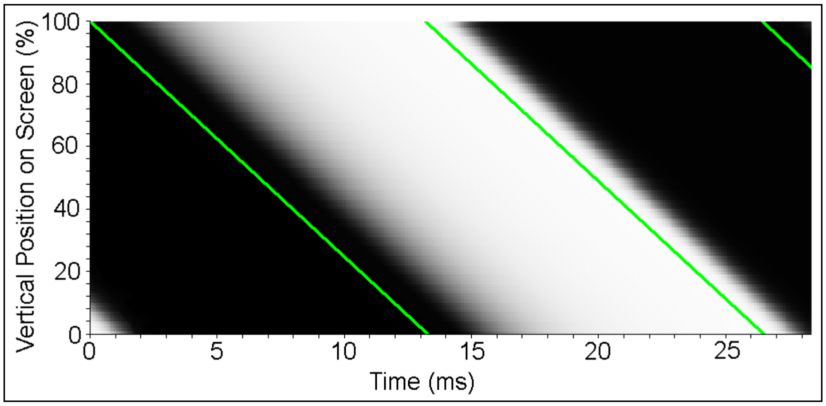

Figure 1: The time-domain response of an example conventional LCD panel alternating between black and white at 75Hz. The vertical axis shows the vertical position on the LCD panel. The horizontal axis shows time. The thin diagonal line represents the addressing of each row of the LCD.

3.5 LCS Duty Cycle

Most driving electronics for LCS 3D glasses drive the shutters with a 50% duty cycle which is problematic for time-sequential 3D on LCDs. In our previous work [1] we showed that reducing the LCS duty cycle can improve compatibility with the time-sequential 3D method.

3.6 Synchronization

In order for time-sequential 3D video to work correctly on a particular display, it is necessary for the display's update of video frames to synchronize with the input video signal. Somewhat surprisingly some commercial displays do not synchronize to the incoming video signal and instead resample the signal to the display's own native frequency (usually ~60Hz) – this resampling process usually destroys the time-sequential 3D video signal.

4. EXPERIMENTAL METHOD

In this study we attempted to test a display representing each of the three technologies described earlier. For the 100/120Hz LCD technology we tested a Sony "KDL46XBR" (46" LCD). For the BFI technology we tested a BenQ "FP241WZ" LCD. Unfortunately we were unable to obtain access to an LCD which used backlight modulation for our tests. Philips did commercially release a range of LCD HDTVs which incorporated a modulated backlight (under the trade name Aptura), however these had been discontinued when we began our testing [7] and we were unable to locate any second-hand displays for testing purposes.

Equipment used for testing included: two custom-built photodiode sensor pens (based on an Integrated Photomatrix Inc. IPL10530 DAL), an oscilloscope (a TiePie Engineering Handyscope HS3 digital USB oscilloscope), and a custom-built LCS 3D glasses driver box capable of adjustable phase and duty cycle. Equipment used to generate the time-sequential 3D video signals consisted of a small form factor PC fitted with a stereoscopic capable graphics card (NVIDIA 6600GT). Software on the PC consisted of Windows XP, Microsoft Powerpoint, the NVIDIA 3D Stereo Driver and JPS Viewer [8], and Powerstrip [9]. The test equipment layout is shown in Figure 2.

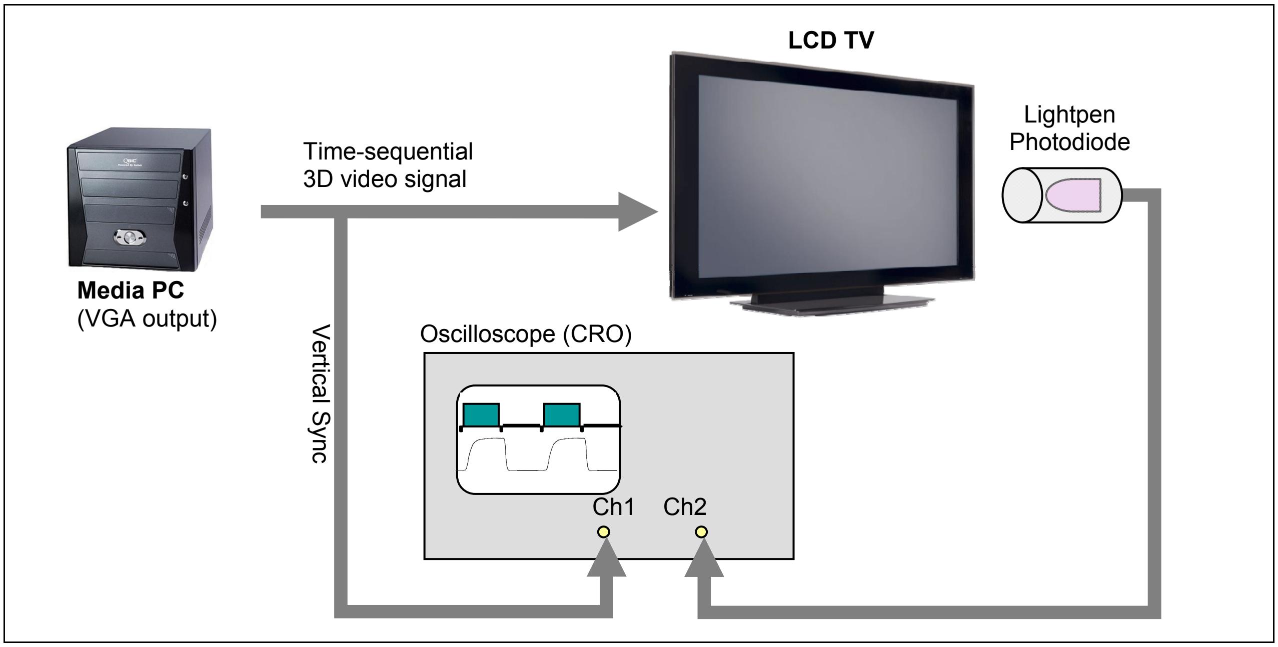

Figure 2: Schematic diagram of the experimental setup.

Test signals consisted of alternating sequences (at frame rate) of ‘red and black’, ‘blue and black’, ‘green and black’, or ‘white and black’ (i.e., in the case of ‘red and black’, one frame of red, followed by one frame of black, and repeat). Each display was tested to establish: (a) whether the output frame rate of the display synchronized with the incoming video signal, (b) whether there was electronic crosstalk between alternate frames, (c) the maximum frequency at which the display would work in stereo, and (d) the time-domain response of the display (to establish pixel response rate, etc). Only the VGA input of the displays was used - the DVI-D and HDMI input connections were not tested because a method of extracting the vertical sync signal from these interface cables was not available.

A custom written Matlab program was used to simulate and characterize 3D compatibility and calculate the crosstalk present on each display. This program was an improved version of the program previously used to simulate the operation and crosstalk performance of Plasma displays [2].

5. RESULTS

The test and simulation results for the tested LCD technologies (BFI and 120Hz refresh) are detailed below.

5.1 Black Frame Insertion

The first thing that should be noted about the particular BFI LCD display that we tested is that it did not synchronize to the incoming video signal. This is a requirement for correct time-sequential 3D operation so this particular display would not be able to be used for time-sequential 3D regardless of its other properties. In order to establish whether BFI had any advantages or disadvantages for time-sequential 3D, the monitor was simulated as if it did synchronize. The time-domain response of the BFI LCD is shown in Figure 3. The (BFI) black frames inserted by the display are indicated by the text labels. With this particular monitor the amount of BFI (or more correctly the duty cycle of the black frames) could be adjusted, from its maximum shown in Figure 3 to a minimum of zero (off). The more BFI that was selected, the dimmer the display became.

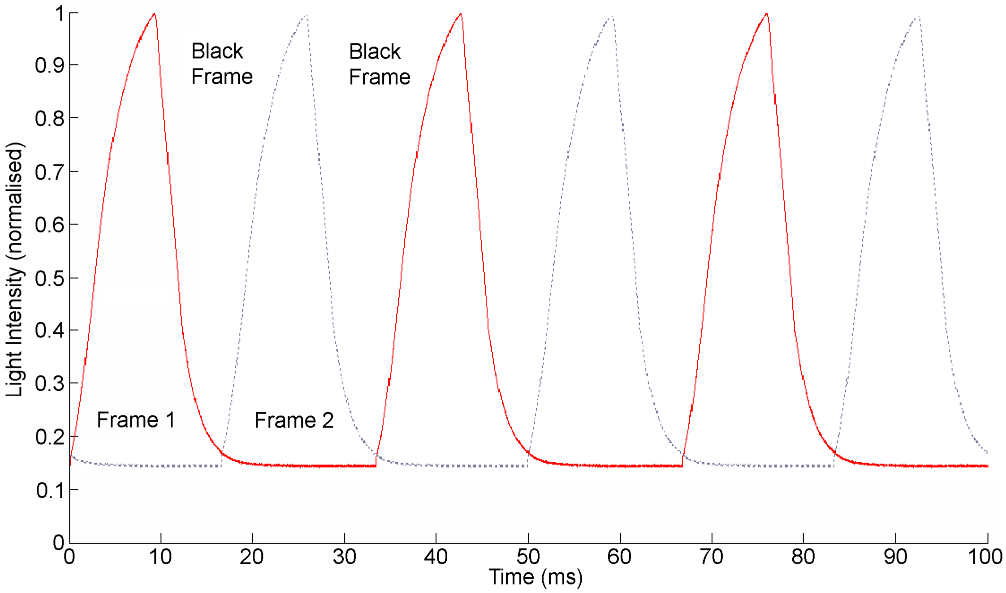

Figure 3: The time-domain response of the example BFI LCD operating at 60Hz. The vertical axis shows normalized light intensity. The solid red trace shows the display being driven with an alternating sequence of black and white input frames. The second dotted trace is the first trace delayed by one frame to show the existence of the (BFI) black frames inserted by the display.

Due to the scan-like image update method of LCDs a more useful way of representing the spatio-temporal output of the LCD is shown in Figure 4. With this particular figure it is easy to see the combination of the sequence of left and right perspective images, the introduction of the inserted black frames (BFI), and the scan-like image update method. It should be noted at this point that due to a technical oversight, the exact image update method of this BFI display was not measured; however we believe this figure to be a reasonable estimate of its operation with this display. It can be seen that the black "BFI" bands do a good job of separating sequential frames, however the presence of the scan-like image update method complicates matters for time-sequential 3D.

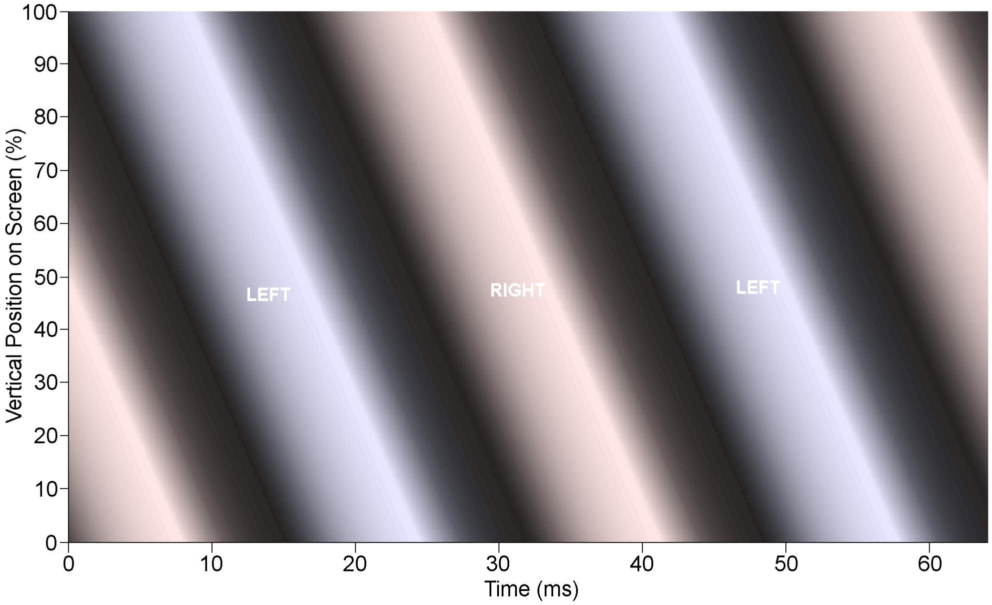

Figure 4: The spatial- and time-domain response of the example BFI LCD operating at 60Hz. The vertical axis shows the vertical position on the screen and the horizontal axis time. The LEFT and RIGHT labels and tinting represent a sequence of left and right perspective images shown sequentially.

Figure 5 illustrates this complication by showing the spatio-temporal output of the display when viewed through LCS 3D glasses. It can be seen that at the beginning of the shutter open period (for viewing the left perspective image) the right perspective image is still visible at the bottom of the screen, and at the end of the shutter open period the right perspective image is starting to be visible at the top of the screen. This will cause ghosting to be visible at the top and bottom of the screen.

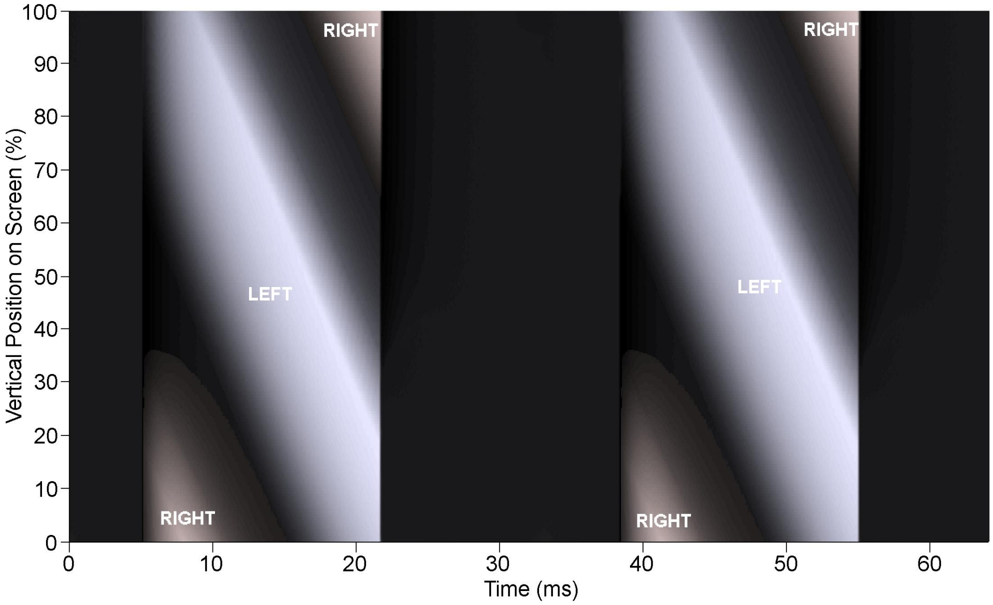

Figure 5: The spatial- and time-domain response of the example BFI LCD operating at 60Hz being viewed through LCS 3D glasses operating at 50% duty cycle. The LEFT and RIGHT labels represent the visibility of left and right perspective images.

Figure 6 shows a calculation of the amount of ghosting that would be visible on the screen when a time-sequential 3D image was viewed through LCS 3D glasses. The two traces on the graph show the amount of ghosting visible on the screen for the two different conditions of BFI on (at maximum) and BFI off – the same display was used for both conditions. With the 'BFI off' case, it can be seen that there is a ghosting minimum at the middle of the screen and

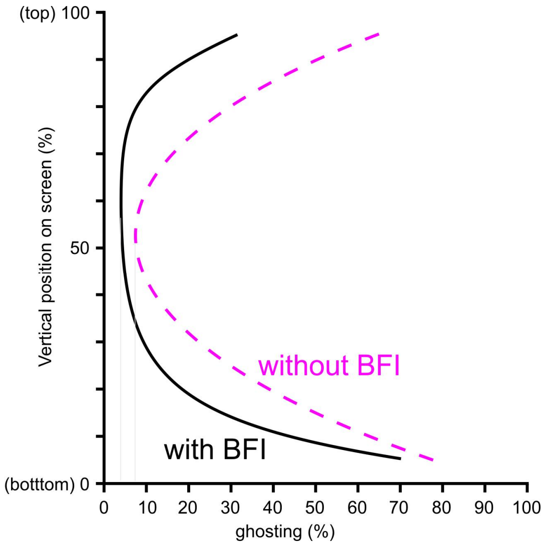

Figure 6: Ghosting simulation results for the BFI LCD monitor with BFI turned on and off. The vertical axis is the vertical position on the screen and the horizontal axis is the calculated amount of ghosting.

ghosting gets worse at the top and bottom of the screen. This is consistent with our previous work [1]. With the 'BFI on' case it can be seen that the ghosting minimum is lower than the previous case and also wider meaning that there would be less ghosting visible across more of the display. However, ghosting does still increase at the top and bottom of the display. Unfortunately it was not possible to visually validate these simulation results due to the fact that the tested monitor did not synchronize to the incoming video signal.

One other thing worth commenting on with this particular display is that the maximum frame rate video signal it was able to accept is 60Hz - it is not capable of accepting a 120 or 100Hz signal. A frame rate of 100 or 120Hz is usually considered necessary for flicker-free time-sequential viewing.

5.2 120Hz Refresh

The first thing that should be noted about the tested 120Hz LCD is that it is not possible to input a raw 100Hz or 120Hz video signal – it is only capable of receiving a signal up to 60Hz vertical frequency. For the display's 120Hz modes, internal electronics in the display interpolate extra intermediate frames between the original 60Hz frames. As discussed earlier, this is designed to reduce the presence of image smear (also known as motion blur). Unfortunately this interpolation (or frequency doubling) process is not compatible with a time-sequential 3D video signal. Additionally with this display the 120Hz mode did not activate when using the VGA input.

The time domain response of the tested 120Hz LCD is shown in Figure 7. The drive signal in this case is a 60Hz video signal alternating between white and black frames. The solid blue trace shows the actual light output of the display. It can be seen that the dotted red trace (which represents the upper envelope of the first trace) alternates between two states (black and white) at 60Hz as expected. The additional regular dips (approximately every 6.3ms) in the blue solid trace are unsynchronized with the input video signal. The dips might be an attempt to improve motion reproduction, but since they are unsynchronized with the video rate they would not have a repeatable effect on time-sequential 3D display. The ghosting results of this monitor (operating at 60Hz) would therefore be very similar to the "without BFI" curve of Figure 6.

The spatio-temporal graphs have not been produced for this display since it could not be driven directly in 120Hz, and the 60Hz results would have been very similar to the results previously published [1].

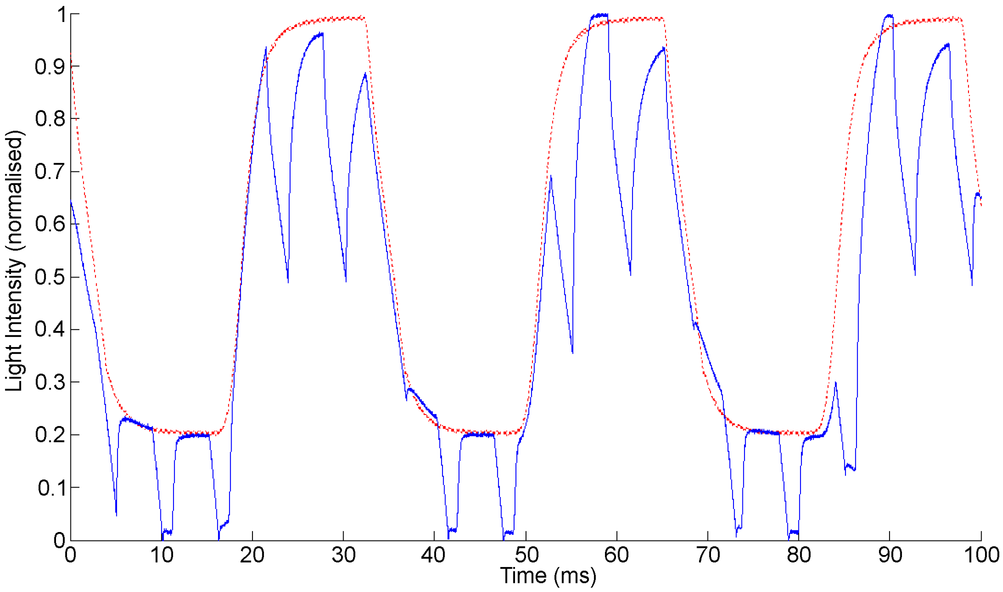

Figure 7: The time-domain response of the example 120Hz LCD operating at 60Hz. The display was being driven with an alternating sequence of black and white input frames. The blue solid trace shows the actual light output of the display. The red dotted trace indicates the upper envelope of the first trace.

5.3 Modulated Backlight

As indicated earlier, we were unable to obtain a modulated backlight LCD for testing during this project. Readers who are interested in considering this topic further are referred to Liou, et al [6].

6. DISCUSSION

Table 1 provides a tabular summary of the three technologies discussed in this paper and the compatibility or incompatibility of the various display properties as embodied in commercially released displays. The main problem of all of these displays is their inability to accept a true 120Hz video input signal. This is determined by the video input electronics and the bandwidth of the input video interface. Even if the 'maximum input video rate' problem was overcome, the scan-like image update method of most displays would still likely cause some problems for time-sequential 3D compatibility, although this seems to be less of an issue for BFI and modulated backlight displays. The details for the modulated backlight column in the table are extrapolated from product specifications and technical papers [3][4][5][6].

Table 1: A summary of the important LCD and LCS properties and compatibility or incompatibility for each of the three display technologies discussed in this paper.

	Black Frame Insertion	120Hz Refresh	Modulated Backlight
Native Polarization	**O** easily overcome	**O** easily overcome	**O** easily overcome
Maximum Input Video Rate	× 60Hz only	× 60Hz only	× 60Hz only
Maximum Display Refresh Rate	× 60Hz only	✓ 120Hz	× 60Hz only
Pixel Response Time	✓ short	✓ short	✓ short
Synchronization	**O** the particular display we tested didn't synchronize but this could be overcome with other displays	✓	✓ probably OK
Image Update Method	× the 'scan-like' image update method causes time-sequential 3D compatibility problems	× the 'scan-like' image update method causes time-sequential 3D compatibility problems	× the 'scan-like' image update method will probably cause some problems with time-sequential 3D compatibility
LCS Duty Cycle	**O** reducing the duty cycle would be beneficial	**O** reducing the duty cycle would probably be beneficial	**O** reducing the duty cycle would probably be beneficial

Key: ✓ = this particular property does not cause any problems with time-sequential 3D compatibility for this display type.
× = this particular property is a problem for time-sequential 3D for this display.
O = this particular property may cause a slight problem with time-sequential 3D compatibility but it is easily overcome.

7. CONCLUSION

Unfortunately our investigations indicate that unless a commercially released LCD TV specifically designates 3D compatibility, it is highly unlikely to be capable of producing flicker-free low-ghost stereoscopic images using the time-sequential 3D method. Furthermore regular 120Hz LCD TVs (without a 'Stereoscopic 3D Compatible' designation) are unlikely to provide improved time-sequential 3D compatibility compared to regular LCD monitors - despite the enticing similarity to the "120Hz 3D" title. The results of the project show that black frame insertion does provide some improvement of 3D compatibility of LCDs but not to a sufficient level to produce flicker-free ghost-free 3D results.

It should be noted that while this manuscript was being finalized, but after the research work was completed, Viewsonic and Samsung each released 22" LCD monitors which are capable of being used for time-sequential 3D viewing in concert with the NVIDIA GeForce 3D Vision LCS glasses [10]. At this point it is not clear what technologies they have implemented to achieve 120Hz time-sequential 3D, however they have certainly increased the maximum input video rate to 120Hz and implemented some other modifications from conventional LCD technology.

It is hoped that more LCDs will be released with stereoscopic 3D compatibility – which will be achieved by addressing the limitations discussed in this paper.

8. ACKNOWLEDGEMENTS

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