7.3: Solving the problem of pixel defects in matrix displays based on characteristics of the human visual system

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Abstract

Manufacturing active matrix displays without pixel defects or repairing all defect pixels is technically not possible at this moment. This paper presents a totally new approach: defects are made invisible to the user of the display by using pixel-data-processing algorithms based on characteristics of the human visual system.

1. Introduction

Active Matrix LCD displays have replaced traditional CRT displays over the last few years. With this type of displays, each pixel has its own individual transistor that controls the backlight shining through that pixel (see figure 1). Occasionally, these individual transistors will short, or otherwise malfunction, resulting in a defective pixel. There are two phenomena which characterize a defective LCD pixel: a "bright" defect pixel, which appears as one or several randomly-placed red, blue and/or green pixel elements on an all-black background; or a "missing" or "dark" defect pixel, which appears as a black dot on all-white backgrounds. With ever increasing resolution of displays the number of defect pixels in a display increases accordingly. State of the art processes are capable of producing displays with faulty transistor rate no more than one part per 2 million. Fixing the transistor itself is currently not possible after assembly.

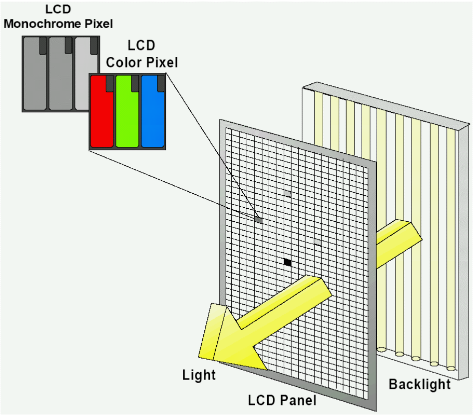


Figure 1: working principle of transmissive AMLCD

In applications such as medical imaging this defect ratio can cause problems. A five Mega Pixel LCD panel for instance, contains 15 million individual sub pixels (3 sub pixels per pixel), each having an individual driving transistor. This means that a five Mega Pixel display could have around 8 failing pixels. Especially "bright" pixels are extremely visible and often very annoying for the user of the display. There exist corrective measures such as "killing" a defective transistor using a laser [1]; however, this just turns a "bright" pixel into a less visible "dark" pixel. For some applications such as medical imaging all "bright" pixels therefore are transformed into "dark" pixels using this laser technique.

This paper describes a totally different solution for the defect pixel problem. By using a pixel-data-processing algorithm based on characteristics of the human visual system we are able to visually mask "missing" pixels. Although this method cannot repair the pixel defects itself, it makes "dead" pixels invisible for the user of the display.

2. Material & methods

The optical system of the human eye [3] comprises three main components (see figure 2): the cornea, the iris and the lens. The cornea is the transparent outer surface of the eye. The pupil limits the amount of light that reaches the retina and it changes the numerical aperture of the optical system of the eye. By applying tension to the lens, the eye is able to focus on both nearby and far away objects.

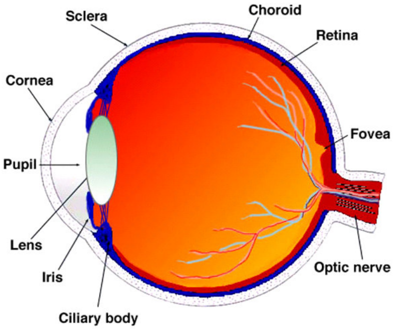


Figure 2: schematic structure of the human eye

The optical system of the eye is very complex but the process of image formation can be simplified by using a "black-box" approach. The behavior of the black box can be described by the complex pupil function: $P(x,y) \cdot \exp[-i(2\Pi/\lambda) \cdot W(x,y)]$. In this formula i stands for $\sqrt{-1}$ and λ is the wavelength of the light. The pupil function consists of two parts: the amplitude component $P(x,y)$ which defines the shape, size and transmission of the black box; and the wave aberration [4] $W(x,y)$ which defines how the phase of the light has changed after passing through the black box.

Once the nature of the light (that passed through the black box, in this case the eye) is known, the image formation process can be described by the point spread function (PSF). The PSF describes the image of a point source formed by the black box. This can be represented by projecting an exceedingly small dot of light, a point, through a lens. Even with a perfect lens system this image will not be a point. This is because the lens system has finite dimensions are therefore diffraction of light takes place at the edges. Moreover, most lenses, including the human lens, are not perfect optical systems. As a result when visual stimuli are passed through the cornea and lens the stimuli undergo a certain degree of degradation or distortion. One typical degradation effect is the introduction of blur. The PSF of the eye can be calculated using the Fraunhofer approximation: $PSF(x',y') = K \cdot \left| FT\{P(x,y) \cdot \exp[-i(2\Pi/\lambda)\, W(x,y)]\} \right|^2$ where FT represents the two-dimensional Fourier transform, usually denoted as $F(x',y') = FT\{f(x,y)\}$, and K is a constant. The $|\;|$ represents the modulus-operator. In case of the human eye, the PSF describes the image of a point source on the retina. Figure 3 shows some examples of typical PSF for small pupil size (1mm).

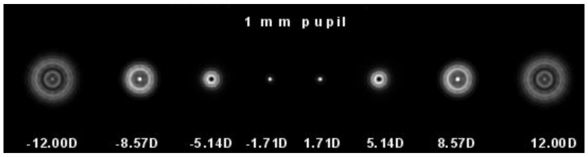


Figure 3: typical PSF for small pupil size

Based on the PSF of the optical system the response or expected response of the eye to a defective pixel can be mathematically described. The defective pixel is treated as a point source with an "error luminance" value dependent on the defect itself and the image data that should be displayed at the defect location at that time. For instance if the defective pixel is driven to have luminance value 23 but due to the defect it outputs luminance value 3, then this defect is treated as a point source with error luminance value –20. It is to be noted that this error luminance value can have both a positive and a negative value. Suppose that some time later this same defective pixel is driven to show luminance value 1 but due to the defect it still shows luminance value 3, then this same defective pixel will be treated as a point source with error luminance value +2.

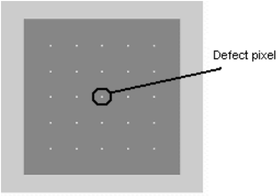


Figure 4: 5x5 pixel area with defect and 24 masking pixels

As described above, this point source with a specific error luminance value will result in a response of the eye as described by the PSF [2]. Figure 5 shows an example of the image projected on the retina of 3x3 equally driven LCD pixels. Because this response is typically not a single point, it is possible to use pixels and/or sub pixels in the neighborhood of the defective pixel to provide some image improvement. These neighboring pixels are called masking pixels and can be driven in such a way as to minimize the response of the eye to the defective pixel. This is achieved by changing the drive signal of the masking pixels such that the superposition of the image of the masking pixels and the image of the defective pixel results in a lower or minimal response of the human eye. In this paper we used a 5x5 pixel area to demonstrate the performance of our algorithm. In figure 4 the defect pixel is located in the center of this area and around the defect we use 24 LCD pixels to mask the defect.

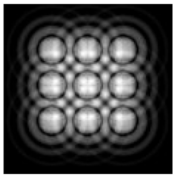


Figure 5: image of 3x3 LCD pixels as projected on the retina

To evaluate the visual performance of our algorithms we always drive the defect pixel with value zero (so totally) off and use the masking pixels to make this defect invisible.

3. Results

To make the mathematical computations somewhat easier we assume that the user has a perfect eye (20/20 vision). This means that the PSF is regularly shaped and can be easily analytically described by means of the diffraction-limited PSF. The PSF of a diffraction limited optical system is given by (in polar co-ordinates):

$$PSF(r') = \left[2 \cdot \frac{J1(r')}{r'} \right]^2$$

where J1 is the Bessel function of the first kind and r' is given by $r' = r \cdot \Pi D / \lambda f$ and where D is the pupil diameter, f is the focal length and λ is the wavelength of the light.

Figure 6 shows the theoretical performance of our masking algorithm applied to a five Mega Pixel display (2560x2048 pixels and 21 inch diagonal) and for diffraction limited PSF and viewing distance of around 30cm. On the left-hand side is the original eye-response of the pixel defect without any correction. The right-hand side shows the eye-response with our masking algorithm applied. An extra complication is that the PSF depends on the pupil size. In the diffraction-limited situation the PSF becomes larger when the pupil size decreases. In figure 6, scale 6 corresponds to medium pupil diameter (around 5mm) and scale 12 corresponds to small pupil diameter (around 3mm). In normal ambient light conditions the pupil diameter will be between 3mm and 5mm.

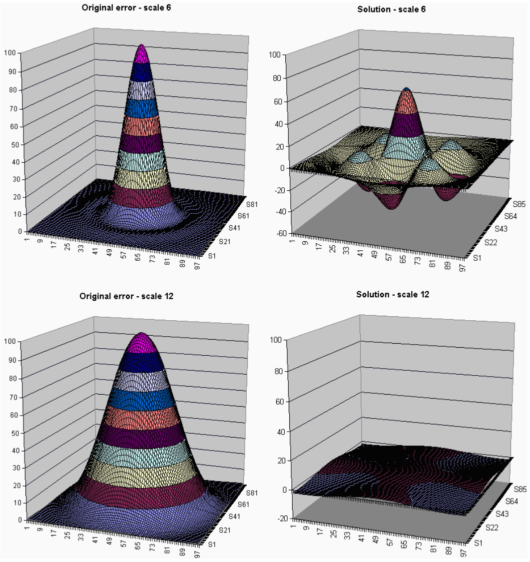
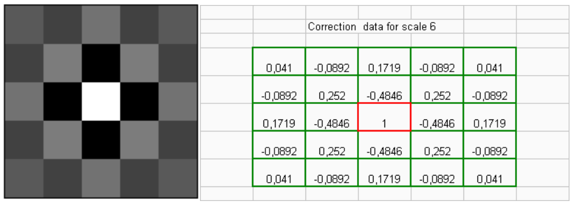


Figure 6: masking performance

Figure 6 clearly indicates that our algorithms are able to mask the defects very well. Note that these results where obtained for viewing distance 30cm, which is very close and represents a worst-case situation. When we increase the viewing distance to a more typical 60cm then he center positions of the masking pixels as projected on the retina will be twice as close to each other. This will also mean that it will be much easier to compensate for the defect as there will be more overlap in the projected PSF of the masking pixels and the defect.

From recent practical results (a small user test) we have found that for viewing distance of more than 50cm it is extremely difficult to see the defect pixels with masking algorithms applied and this independent of ambient light conditions. The fact that the PSF depends on the pupil size does not seem to be a problem since user tests suggest that the performance of our algorithm remains very good if we always use the same pupil size (4mm) independent of the actual pupil size of the user. Also we visually tested our masking algorithms both on monochrome and color displays and for both low-resolution (1024x768) and high-resolution (2560x2048) displays and projection systems. In all situations we found a significant decrease in the visibility of pixel defects and in most situations the defects even were completely invisible from a normal viewing distance.



Correction data for scale 6

0,041	-0,0892	0,1719	-0,0892	0,041
-0,0892	0,252	-0,4846	0,252	-0,0892
0,1719	-0,4846	1	-0,4846	0,1719
-0,0892	0,252	-0,4846	0,252	-0,0892
0,041	-0,0892	0,1719	-0,0892	0,041

Figure 7: example correction values for masking pixels

As example figure 7 shows typical correction values needed for the masking pixels. Remember that the center pixel is the defect and therefore we assigned it value 1. The other pixels are masking pixels; a value -0.4 for instance means that the masking pixel should be driven with 40% less luminance to compensate for the defect. Note that both negative and positive correction values are required for high-quality masking of the defect.

An additional advantage of the described masking algorithms is that they can be implemented efficiently and cost-effectively in a microprocessor, a DSP or FPGA. In principle the processing required is equivalent to a non-linear image-processing filter. The kernel size of this non-linear filter depends on the number of masking pixels that are used to compensate for the defective pixels. Typical kernel sizes are 3x3 and 5x5 LCD pixels.

A prototype 5 Mega Pixel display system has been developed including the defect pixel masking algorithms implemented inside an FPGA in the display. In our prototype display the correction algorithms are applied in real-time to all images and video being displayed on the monitor.

4. Conclusion

Producing displays without pixel defects or repairing defect pixels is technically not possible at this moment. This paper presents a totally new approach to solve this problem: defects are made invisible for the user of the display by using characteristics of the human eye. Moreover, our methods can be implemented very efficiently and cost-effectively as pixel-data-processing algorithms inside the display in for instance an FPGA, a DSP or a microprocessor.

The described techniques are valid for both monochrome and color displays and projection displays ranging from high-quality medical displays to consumer LCD-TV applications. Therefore we believe that this paper can influence the design of future active matrix LCD display electronics.

5. Acknowledgements

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6. References

[1] Defective Pixels in Liquid Crystal Displays, NEC whitepaper, http://www.necdisplay.com/support/css/Techlibrary/whitepaper_dead_pixel_wp.pdf

[2] Dynamic Retinal Image Reconstruction of the Human Eye, 5th International Symposium on Signal Processing and its Applications, Brisbane, Australia, 23rd-25th August 1999, C. Chao, D.R. Iskander, M.J. Collins, B. Davis and M. Bennamoun

[3] EE368b Image and Video Compression Human Visual Perception no. 2, Anatomy of the human eye, Bernd Girod, http://www.stanford.edu/class/ee368b/Handouts/09-HumanPerception.pdf

[4] Measurement of the axial wavefront aberrations of the human eye, Opthal. Physiol. Opt., 5(1): 23-31, 1985, G. Walsh and W.N. Charman