Human vision-based algorithm to hide defective pixels in LCDs

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ABSTRACT

Producing displays without pixel defects or repairing defective pixels is technically not possible at this moment. This paper presents a new approach to solve this problem: defects are made invisible for the user by using image processing algorithms based on characteristics of the human eye.

The performance of this new algorithm has been evaluated using two different methods. First of all the theoretical response of the human eye was analyzed on a series of images and this before and after applying the defective pixel compensation algorithm. These results show that indeed it is possible to mask a defective pixel. A second method was to perform a psycho-visual test where users were asked whether or not a defective pixel could be perceived. The results of these user tests also confirm the value of the new algorithm.

Our "defective pixel correction" algorithm 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 also valid for both monochrome and color displays ranging from high-quality medical displays to consumer LCD-TV applications.

Keywords: defective pixel, active matrix display, hide, compensate, human visual system

1. INTRODUCTION

Within LCD displays, each pixel has its own individual transistor that controls the transmittance of 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 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 "dead" 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 no more than one part per 2 million. Fixing the transistor itself is currently not possible after assembly. This means that for example a 5 megapixel medical display system with five million pixels (and therefore 15 million subpixels) will have on average seven defective pixels.

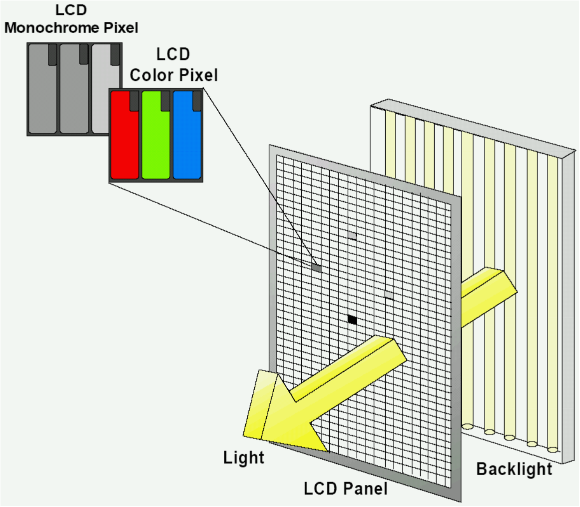


Figure 1: principle of active matrix displays

Defective pixels are often very annoying to the users of a display system and for many applications such as LCD TV, digital cinema and desktop monitors; the existence of defective pixels seriously degrades the image quality. For other applications such as medical imaging the existence of defective pixels could even influence the critical decision making process and therefore result into wrong diagnosis. In mammography, e.g, defective pixels could interfere with or mask subtle image features such as micro-calcifications [6].

There exist corrective measures such as "killing" a defective transistor using a laser [1, 2]; however, this technique just turns a "bright" pixel into a less visible "dark" pixel. For demanding applications such as medical imaging all "bright" pixels are systematically transformed into "dark" pixels using this laser technique. Another method that can be used for critical applications is storing the exact location of each defective pixel inside the display [3]. This information can then be retrieved automatically or on demand of the user and the exact location of each defective pixel can be visualized for the user of the display (see figure 2). Providing the user with knowledge on the existence and exact location of defective pixels can avoid that the outcome of the task is influenced by the defects.

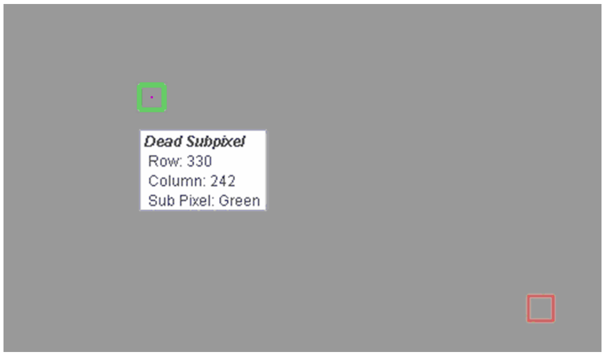

Dead Subpixel
Row: 330
Column: 242
Sub Pixel: Green

Figure 2: visual map of defective display pixels

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 hide "missing" pixels. Although this method cannot repair the pixel defects itself, it makes defective pixels invisible for the user of the display.

2. COMPENSATION ALGORITHM

The optical system of the human eye comprises three main components: 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.

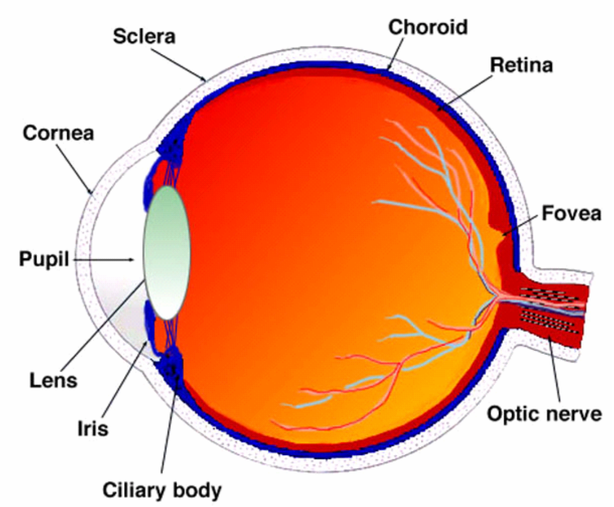


Figure 3: main components of the human eye

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 [4]: $P(x,y) \cdot \exp[-i(2\Pi/\lambda) \cdot W(x,y)]$. 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 [5] $W(x,y)$ 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 and 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 stands for 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 4 shows some examples of typical PSF for small pupil size (1mm) and for multiple degrees of defocus of the eye. The right hand side of figure 4 shows an example of a measured PSF of a human eye this time in an older subject with more aberrations. This last example shows that very often the PSF is not point-symmetric and therefore difficult to model analytically.

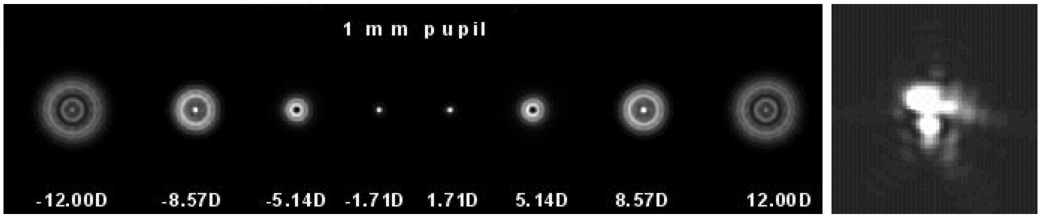


Figure 4: examples of point spread functions of a human eye

Based on the PSF of the optical system the response or expected response of the eye to a defective pixel can be mathematically described. Therefore 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. Supposing 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.

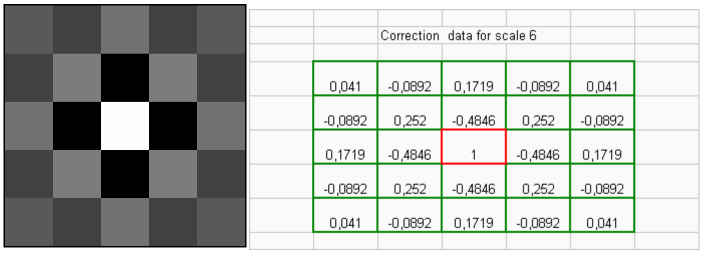
As described above, this point source with a specific error luminance value will result in a response of the eye as described by the PSF. Because this response is typically not a single point, it is possible to use pixels and/or sub pixels in the neighborhood of the defective pixel to provide some image 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. For this paper we used a 5x5 pixel area to demonstrate the performance of our algorithm. The defect pixel is located in the center of this area and around the defect we used 24 pixels to mask the defect. To evaluate the visual performance of our algorithms we always drive the defect pixel with value zero, simulating a “dead” pixel, and use the masking pixels to make this defect invisible.

To make the mathematical computations somewhat easier we assumed 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

$r' = \frac{\pi D}{\lambda f} \cdot r$ and where D is the pupil diameter, f is the focal length and λ is the wavelength of the light.

As an example figure 5 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.



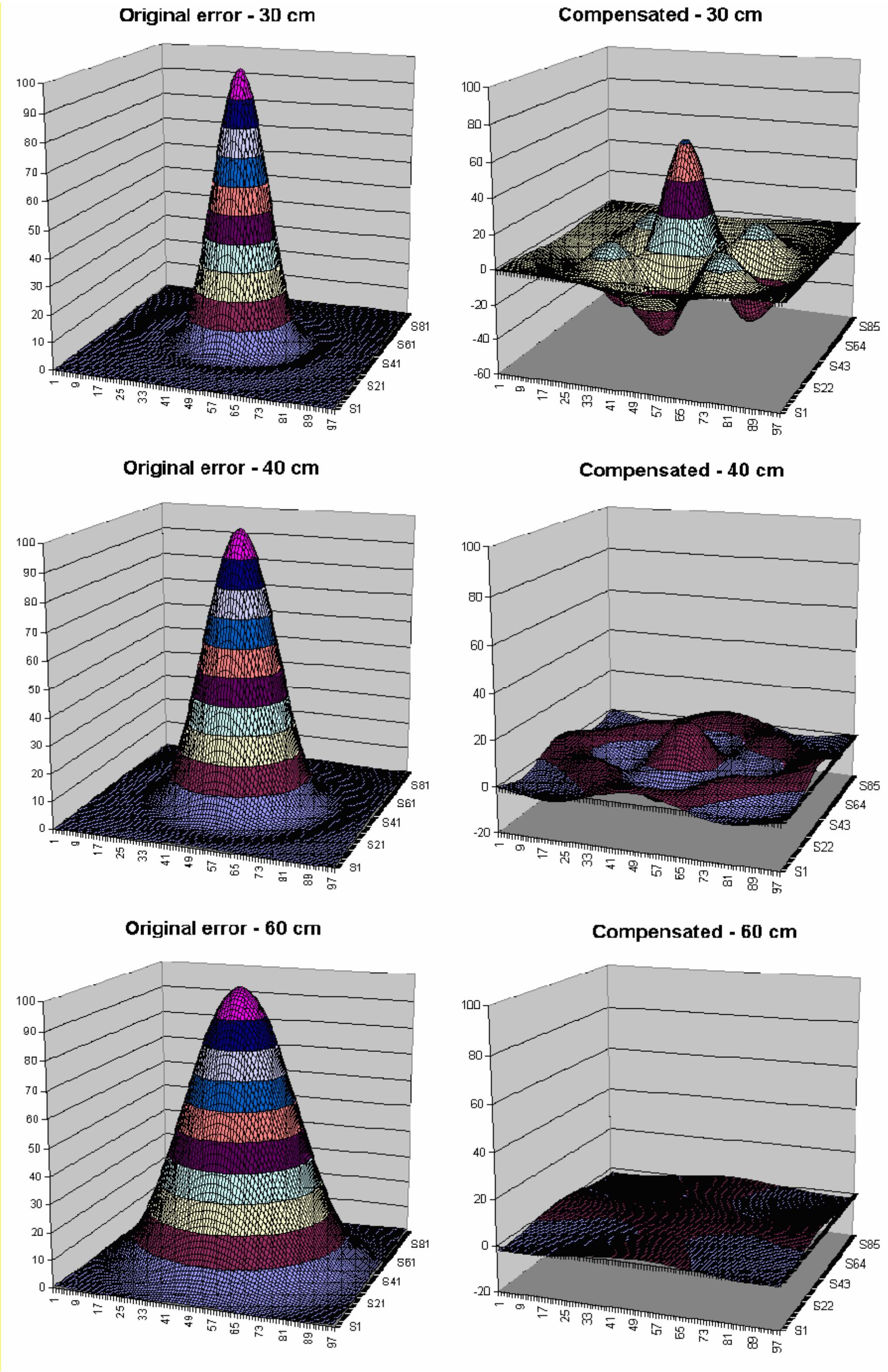
Correction data for scale 6

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 5: example correction values for masking pixels

3. PERFORMANCE ANALYSIS

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 30cm-60cm. 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.


Original error - 30 cm

Compensated - 30 cm

Original error - 40 cm

Compensated - 40 cm

Original error - 60 cm

Compensated - 60 cm

Figure 6: theoretical performance of compensation algorithm

Figure 6 clearly indicates that our algorithms are able to mask the defects very well. Note that the top 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 (bottom plot in figure 6) then the 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.

To verify the performance of our algorithm a small psycho-visual test was performed. Test patterns were shown to a group of 11 people on a 21 inch color display with resolution 1600x1200 pixels and brightness 300 cd/m². These test patterns consisted of a background and a central rectangle of slightly higher grayscale value (see figure 7). In total 24 test patterns were shown to each user and this in a random order. The gray scale values of the rectangles were set to 16, 32, 64, 96, 128, 160, 192 and 240 respectively. For each of these grayscale values three test images were created: one image that did not contain a defective pixel, one test image that contains an uncorrected defective pixel and one test image that contains a defective pixel that has been compensated using our algorithm. The location of these defective pixels is chosen randomly within the central rectangle. People were asked if they could see a defective pixel inside the rectangle or not (yes or no answer) when looking from a distance of 40 cm. There was no time limit to answer. These psycho visual tests were done in normal office lighting conditions.

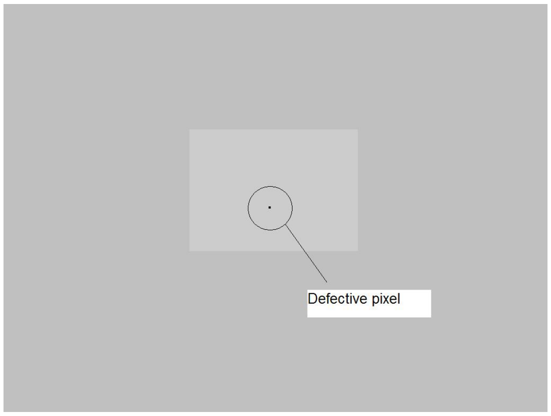


Figure 7: example of test pattern used for psycho visual test

Results of the psycho visual test are shown in figure 8. This graph shows how often users reported that a defective pixel was visible and this for the three situations (no defect present, uncompensated defect present, and compensated defect present). It can be seen from figure 8 that there are false positives (people think that a defect is present while this is not the case). We observe a false positive fraction of around 5%. For the test images where there was an uncompensated defective pixel present, people reported around 65% of these defects. On the other hand, test images with our compensation algorithm applied resulted in still visible defects in only around 12% of the cases. The error bars are also included in the graphs.

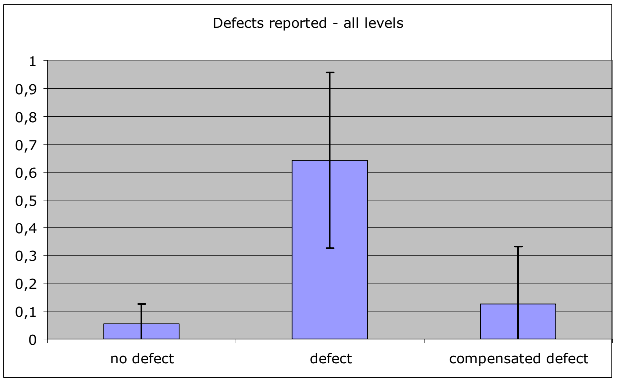


Figure 8: defects reported (average all video levels)

It is to be expected that the compensation algorithm will have the biggest effect for mid-tone grayscales. Reason is that for low grayscales defects just will not be visible because they don't differ a lot from the actual signal. Indeed: a dead pixel on a dark background will be very hard to see. On the other hand, for the highest grayscales the compensation will not be as effective anymore since it is not possible to increase the driving signal of the masking pixels outside the available dynamic range of the display. Therefore we also made the same analysis where we excluded very low and very high grayscale values. These results are shown in figure 9.

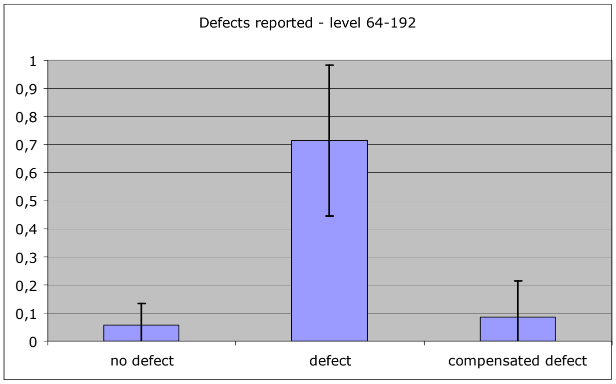


Figure 9: defects reported (video levels 64-192)

Even with the very limited psycho visual user test done with a group of 11 people the results are already statistically significant if we exclude lowest and highest grayscales. If we would increase the number of test subjects then the error bars would decrease accordingly and also the results where all video levels are included would be most likely statistically significant. A more extensive psycho-visual test will be performed in the near future.

Results for individual video levels are shown in figure 10. As could be expected, for low video levels only a limited fraction of defective pixels can be perceived even if no compensation is applied. This is normal since for low video levels the difference between a defective and non-defective pixel is very small. The higher the video level the higher the fraction of uncompensated defective pixels that is reported. If we look at the compensated defective pixels then we see that the compensation works extremely well for low video levels, mid range video levels and even high video levels. For video levels lower than 160 not a single test subject reported a compensated defect. For video level 160, about 12% of the compensated defective pixels still are perceived by the users and this increases to around 57% for video level 240. As already indicated with the very high video levels it is not possible to provide the optimal compensation anymore because the neighbors of a defective pixel cannot be driven higher than video level 255. However, the overall conclusion is that the proposed compensation algorithm clearly reduces the fraction of defects that can be perceived by the user of the display.

Figure 10: defects reported for individual video levels

4. CONCLUSIONS

Producing displays without defective pixels or repairing defective 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. Both theoretical simulations and a psycho-visual test have shown the effectiveness of the proposed algorithm.

The described methods can moreover 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 proposed algorithms are applicable to both monochrome and color displays ranging from high-quality medical displays to consumer LCD-TV applications.

5. REFERENCES

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