A Low Power, Passively Cooled 2000 cd/m^2 Hybrid LED-LCD Display

Ulrich Barnhoefer, Moon-Jung Kim, and Mattan Erez

Abstract — *In this paper, we describe a hybrid LED-LCD screen that delivers the same image peak-brightness at 1/2 to 1/20th the power consumption per unit LCD screen area compared to conventional designs. Our architecture is based on an adaptive, spatially controlled LED backlight and a unique algorithm that decomposes the displayed image into LED and LCD components in order to minimize power consumption. In addition to the efficiency gained over current displays, our implementation is also suited for high dynamic range applications, achieving a peak brightness of 2000 cd/m^2 with a 20,000:1 contrast ratio. We introduce, for the first time, implementation details of a spatially adaptive LED-LCD display and describe a novel thermal and electrical design. Our display is comprised of a standard FR4 PCB populated with an array of individually controlled high brightness LEDs, their associated control electronics mounted, and a LCD panel. The use of standard PCB (no metal core) is made possible by carefully designing efficient driver electronics (76% efficiency), introducing thermal channels to a large integrated heat sink implemented as part of the PCB, and employing power-reducing decomposition algorithms. Our prototype is completely passively air cooled, silent, and light[1].*

Index Terms — Display, Backlight, Low-Power, Thermal Management, LED, LCD, High Dynamic Range.

I. Introduction

LCD displays have become a ubiquitous electronics component, from large high-brightness home entertainment displays to small battery-operated mobile displays. Regardless of size or application, power dissipation is a key limiting factor of LCD display performance. In the case of large LCD displays, size and brightness levels are primarily limited by power dissipation and cooling. For example, more than 1 kW are required to achieve 2000 cd/m^2 on a 30" LCD given an efficient fluorescent backlight. While larger sizes and higher brightness are desirable, the power-dissipation by itself, and additionally the cooling technology that would be needed, impede the development of such products with reasonable weight, price, or fan-noise levels. Power consumption is also critical for small, battery-operated, mobile LCD displays. The power consumption associated with the display is a large fraction of the total energy dissipated by mobile devices, often exceeding 50%. Thus, a significant reduction in display power consumption is essential for the continued successful development of mobile devices, enabling a reduction in battery size, and hence, device size, or making possible a substantially longer battery runtime.

In this paper, we detail the development and implementation of prototype hybrid LED-LCD hardware that delivers the same image peak-brightness at 1/2 to 1/20th the power consumption per unit LCD screen area when compared to conventional LCD displays. Our design uses high-brightness LEDs, which typically require exotic active cooling and metal core printed circuit board technology (MCPCB). Careful thermal and electrical design permits the use of low-cost standard FR4 printed circuit boards (PCBs) and enables a solution that can accommodate all system and cooling components on a single board.

In addition to the power-efficiency gained over current displays, this implementation is also suited to improve image quality for high contrast source material. This type of data is becoming increasingly available through new image capture technology [1]-[3]. Our prototype display achieves a peak brightness of 2000 cd/m^2 with a maximum 20,000:1 contrast ratio. An earlier high brightness display is detailed in [4], [5]. In comparison, our prototype requires low power (0.25-0.8 W/in^2), is passively air-cooled, silent (requires no fans), and exhibits a low weight per unit area (less than 17 g/in^2 including power supply). Therefore, it can be manufactured, transported, and used at consumer-level prices and requirements.

In this paper, we make the following contributions:

- We introduce the design and implementation details of a spatially adaptive hybrid LED-LCD display.
- We demonstrate, for the first time, a significant power saving potential for this architecture, which can reach 20-fold for some images.
- We describe the novel thermal and electrical design that permits high integration and design flexibility on a standard FR4 PCB.
- We describe a system that, due to its thermal design, can operate without active cooling with one order of magnitude brightness improvement.
- We discuss potential applications for hybrid LED-LCD displays including high contrast image reproduction and low power scenarios.

[1] This work is supported by Eastman Kodak Company.

U. Barnhoefer, M. Kim and M. Erez are with Stanford University, Stanford, CA 94305, USA (e-mail: barnhoefer@stanfordalumni.org, moonie@stanford.edu, mattan.erez@stanford.edu).

1-4244-0216-6/06/$20.00 ©2006 IEEE

In Section II, we detail the system's electrical and thermal design. In Section III, we introduce the power-reduction enabled by our design. Finally, in Section IV, we conclude with a discussion of the impact of the substantial efficiency improvement and of the new flexibilities in manufacturing and cooling.

II. IMPLEMENTATION, HARDWARE & SYSTEM DESIGN

In this section, we present a novel display hardware that uses a unique backlight, which is designed around an array of LEDs with highly efficient driver electronics. The entire backlight is mounted on a single standard FR4 PCB. A magnified portion of the front and back of the backlight is shown in Fig. 1. Our design is scalable to any size, and we have manufactured a functioning 12.1" prototype display with a 9 x 7 LED array backlight and a 1024 x 768 pixel LCD front panel.

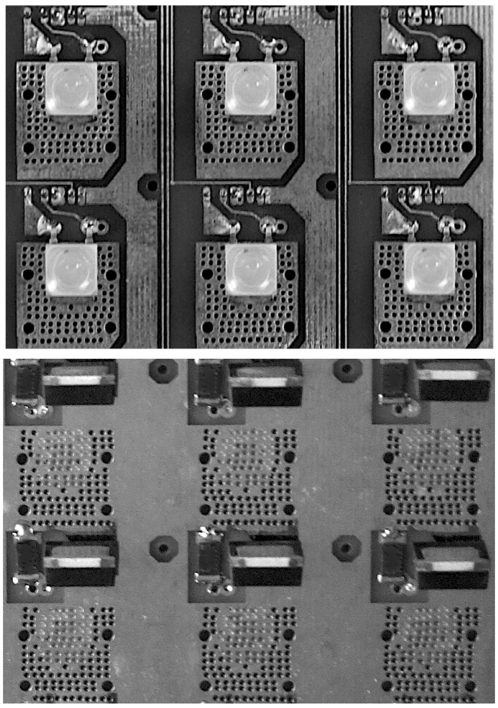


Fig. 1. Zoomed in area of the front (top) and back (bottom) of the LED backlight array showing 6 out of 63 cells. The design is scalable to any size; this prototype is a 9 x 7 array with a 12.1" LCD front panel.

The front of the backlight PCB is populated with high brightness LEDs that exhibit a luminous flux of 40 lumen each. The backlight assembly includes optics and diffuser sheets achieving at peak brightness a measured homogeneous 22,000 cd/m^2 incident on the LCD front panel at the maximum power consumption of 115 W. The combined effect of the optical elements results in an isotropic viewing angle of 53^o for the display system. A detailed description of the optical design is beyond the scope of this paper. When viewed through the LCD front panel, which has a measured peak transmittance of 9%, the effective brightness is 2,000 cd/m^2. This is approximately one order of magnitude higher than conventional LCD displays [6]. The back of the PCB contains the driver electronics that allow independent control of each individual LED with an efficiency of 76%, at all brightness levels. This efficient driver electronics, which despite the added degrees of freedom in control, exhibits in its homogeneous mode the same driver efficiency and similar lamp efficiency as conventional LCD displays. We use pulse-width modulation to control the LED brightness achieving a dynamic range of 1:1000 per LED; the minimum brightness step is determined by the rise-time of the driver electronics. Combined with the 1:200 dynamic range of the LCD front panel, we can display high-contrast 1:20,000 images, where the potential dynamic range of 1:(1000x200) is reduced by approximately one order of magnitude due to internal scattering. The control signals are provided in real time through an FPGA based graphics controller board, which we designed to allow both still-image and video display.

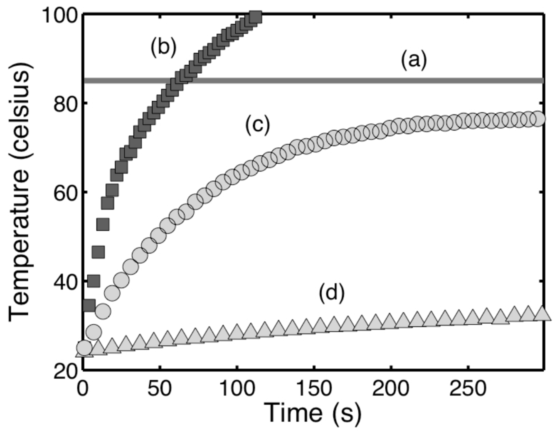


Fig. 2. Passive cooling on a FR4 PCB with no metal core: (a) absolute maximum temperature rating for LEDs; (b) single LED at maximum current of 0.35 A, LED heatsink in air; (c) passive cooling with thermal channels, all 63 LEDs at maximum current (2,000 cd/m^2 screen brightness); (d) passive cooling with thermal channels, all 63 LEDs at 1/10 maximum current (200 cd/m^2 screen brightness). Temperatures were measured at the LED heatsink.

The use of high-brightness LEDs necessitates careful thermal design because the integrated LED heatsink is insufficient. As shown in Fig. 2 (square data points), the absolute maximum temperature rating of 85^{o}C [7] is exceeded within 60 seconds of operation. We present a novel PCB design based on a standard FR4 process that does not require a MCPCB as currently specified by high-brightness LED manufacturers [8]. Instead of relying on an embedded metal layer for cooling, we introduce 134 thermal channels per cell (see Fig. 1) that connect the LED heatsinks with a cooling plane placed on the back of the standard FR4 PCB. The use of a standard PCB greatly reduces cost, and more importantly, increases flexibility in layout. Specifically, the FR4 process allows us to fit the driver electronics and LED in the space provided by one cell, which would be impossible with an MCPCB. Furthermore, it allows us to integrate the entire system on a single board, in contrast to the MCPCB case that makes a multi-board solution inevitable.

Fig. 2 also shows that our FR4 based passive cooling thermal design significantly exceeds the requirements for high brightness LEDs even when all are simultaneously at peak power dissipation, which is not the usual mode of operation. The circular data points present the effect of our new thermal design when all 63 LEDs are at maximum brightness at the same time (0.35A x 63, continuous). The temperature was measured directly at the heatsink. As a reference, we provide a temperature measurement at a more common operating brightness of 1/10 peak (triangular data points), which corresponds to a standard screen brightness of 200 cd/m^2. To passively cool, not only the LEDs, but also the driver electronics, we mount the current-driver modules perpendicular to the PCB, thus keeping driver cooling independent from the LEDs (see Fig. 1, bottom). With all LEDs at peak brightness, we measured a maximum temperature of 90^{o}C at the driver heatsink, well below the driver's maximum rating of 150^{o}C.

Fig. 3. Brightness distribution of the spatially adaptive LED backlight (left) for a sample image (right). This image corresponds to image number 3 in Fig. 4, and achieves a factor of 4.9 in power reduction.

III. POWER SAVING ANALYSIS

In this section, we focus on the power reduction potential of the hybrid LED-LCD display. We provide a new perspective and method of reducing power consumption of LCD displays. We show that our design yields a significant reduction in power dissipation for both conventional and high contrast images compared to conventional LCDs.

The novel LED backlight presented in this paper allows us to break the linear relation between LCD brightness and LCD power consumption. Thus, it is possible to show the same image on the LCD with the same brightness at a fraction of the power. Conventional LCDs operate the backlight at a constant brightness regardless of the actual image being displayed. As a result, the power consumption is independent of the image, and is determined by the peak brightness specified for the design. Using our spatially adaptive backlight, we decrease light production at darker areas of the image, as opposed to increasing front panel attenuation as in conventional designs. To do this, we subdivide the image into blocks (one per LED), and calculate a decomposition into LED brightness and LCD transmittance. Our algorithm minimizes energy consumption by setting at least one LCD pixel of each block to maximum transmittance, allowing for minimal LED brightness. Additionally, the decomposition step ensures a faithful representation of the image. Fig. 3 shows an example of how the adaptive backlight generates light in proportion to actual image brightness. The power-reduction for this example is 4.9 fold.

We analyzed the reduction in power consumption for a total of 53 high dynamic range images [9]-[12] and 67 conventional images [13]. The results for 24 representative images are presented in Fig. 4.

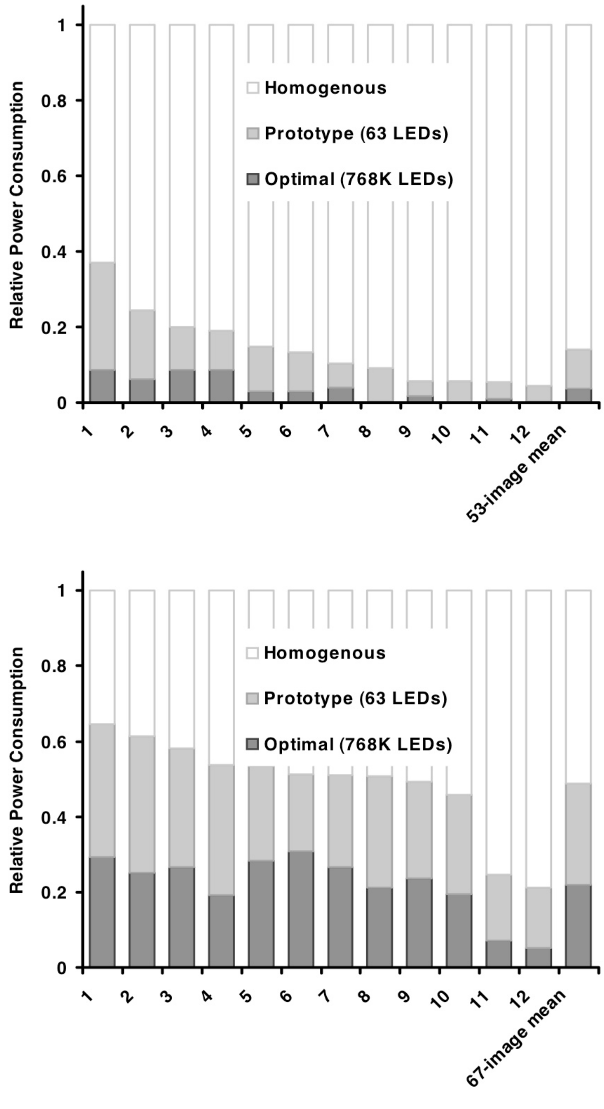


Fig. 4. Measured power reduction of our spatially adaptive LED array backlight (light gray) relative to a conventional homogenous LCD backlight (white) with the same lamp efficiency. As reference is shown the projected lower bound when dedicating a light source to each displayed pixel (dark gray). Top graph: for high contrast images [8]-[11]. Bottom graph: for conventional images [12].

For high dynamic range images, we measured a power reduction ranging from 2.7 to 22 fold with an average of 7.1 fold. When displaying conventional images, the power reduction was on average a factor of 2.3. Thus, the average power consumption (e.g. when displaying video) is reduced from 115 W to 16.2 W and 50 W for high-contrast and conventional material, respectively. The lower energy-saving for conventional images is due to the more severe clipping, which reduces the degree of adaptivity. Fig. 4 also shows the absolute lower bound on energy savings that can be achieved through this technique when dedicating a light source to each displayed pixel (Fig. 4, dark square).

IV. CONCLUSION

We have designed and fabricated a novel spatially adaptive LED based backlight, and demonstrate potential impact in three categories:

(1) Our hybrid LED-LCD display system provides a fundamentally novel perspective on reducing power consumption of LCD displays. Our design achieves a power reduction of approximately 2 fold for conventional images and 3-20 fold for high dynamic range images. The prototype display uses highly efficient driver electronics, which despite the added degrees of freedom in control exhibits in its homogeneous mode the same driver efficiency and similar lamp efficiency as conventional LCD displays.

(2) The techniques presented in this paper are well suited for constructing displays for emerging high-contrast and high-brightness image standards, for the first time, without requiring active cooling and exotic fabrication technology. Following our careful layout scheme and relying on our power-reduction techniques, we envision a 12,000 cd/m^2 passively-cooled high-contrast display using standard FR4 PCBs and existing high-brightness LEDs. This is possible because natural scene (high contrast) video allows conservatively a factor of 3 in power savings with the presented method and newly developed LED technology allows twice the brightness at the same power dissipation and can be driven at higher currents. Thus, 12,000 cd/m^2 can be achieved with our design by only replacing the lamp technology without requirement for additional cooling. The peak power dissipation will also, in this case, not exceed 115W per same area.

(3) The novel physical design allows high-brightness LEDs to be mounted on standard FR4 PCBs, in contrast to current manufacturer specifications calling for the use of MCPCBs. Moving to standard fabrication technology increases the wiring and layout flexibility and permits designers to use well-supported modern CAD tools. Additionally, we can avoid the price premium associated with MCPCBs.

REFERENCES

[1] W. Bidermann, A. El Gamal, S. Ewedemi, J. Reyneri, H. Tian, D. Wile, D. Yang. “A 0.18 μm high dynamic range NTSC/PAL imaging system-on-chip with embedded DRAM frame buffer,” *Proceedings of the IEEE ISSCC*, 2003, pp. 212-488.

[2] Adobe Systems Incorporated, *Photoshop CS2: HDR Capture Feature and 32-bit Color Image Support*, 2005.

[3] G. Ward, “Fast, robust image registration for compositing high dynamic range photographs from handheld exposures,” *Journal of Graphics Tools*, 8(2): 17-30, 2003.

[4] Brightside Technologies, *Product Specifications*, http://www.brightsidetech.com/.

[5] H. Seetzen, W. Heidrich, W. Stuerzlinger, G. Ward, L. Whitehead, M. Trentacoste, A. Ghosh, A. Vorozcovs, “High dynamic range display systems,” *ACM Transactions on Graphics*, Aug. 2004, vol. 23, no. 3, pp. 760-8.

[6] LG-Philips Co. Ltd, *Digital Catalog of LCD Displays,* March 2005, LG_Philips_LCD.pdf at http://www.lgphilips-lcd.com/

[7] Nichia Corporation, *LED specifications*, http://www.nichia.com/product/led.html.

[8] Lumileds Lighting, U.S. LLC, “Thermal Design Using Luxeon Power Light Sources,” *Application Brief*, 2005.

[9] Stanford Vision and Imaging Science and Technology Lab, *HDRI Image Database*, http://pdc.stanford.edu/hdri/.

[10] Industrial Light and Magic, *OpenEXR Sample Images*, http://www.openexr.com/.

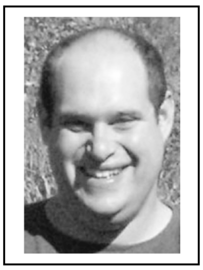
[11] Paul Debevec, *Sample High Dynamic Range Images*, http://www.debevec.org/Research/HDR/.

[12] Munsell Color Science Laboratory, RIT MCSL, *High Dynamic Range Image Database*, http://www.cis.rit.edu/mcsl/icam/hdr/rit_h dr/.

[13] Digital Photography Review, *Conventional Consumer Camera Image Database*, http://www.dpreview.com/gallery/.

Ulrich Barnhoefer received a B.S. and a M.Sc. in Physics from the Technische Universität München, Germany in 1992 and 1998, respectively. He studied part of his graduate degree at the National Center for Microelectronics in Seville, Spain. As a Ph.D. candidate in Electrical Engineering at Stanford University, CA, USA he worked on improving color and noise processing in digital cameras, spectral detection and new display technologies in conjunction with Eastman Kodak Company. His previous industry experience includes design and analysis of integrated electro-optical systems at Siemens and low power wireless systems at Infineon Technologies.

Moon-Jung Kim received a B.S. and a M.S. in Electrical Engineering from Seoul National University, Seoul, Korea, in 1994 and 1996, respectively. As a researcher at ISRC (Inter-university Semiconductor Research Center) at Seoul National University, she worked on compound semiconductor circuits and devices for optical communication and on neural prosthetic devices for biomedical applications. As a Ph.D. candidate at Stanford University, CA, USA, her research focused on CMOS analog circuit design including RF transceiver circuits, high-speed serial links, power converters, and high voltage IO circuits in conjunction with National Semiconductor and Infineon Technologies. She loves teaching.



Mattan Erez received a B.Sc. in Electrical Engineering and a B.A. in Physics from the Technion, Israel Institute of Technology in 1999. He subsequently received his M.S in Electrical Engineering from Stanford University in 2002. His previous experience includes working as a computer architect in the Israeli Processor Architecture Research team, Intel Corporation. As a Ph.D. candidate at Stanford University, CA, USA he participated in the Smart Memories project and is currently leading the Merrimac Stanford Streaming Supercomputer project, where his main areas of interest are architecture and its interaction with the compilation system and the programmer.