Color Display Technology: From Pixels to Perception

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Abstract

Over the past twenty-five years a diversity of color display technologies has evolved to support a wide range of applications including television receivers, computer monitors, cell phones, PDAs, automobile dashboards, aircraft instruments, and even in-car and in-flight entertainment systems. In all product categories consumer's expectations for color display performance have grown at a rapid pace, driving the accelerated development of core display technologies along with supporting color control algorithms and image processing methodology. In this keynote address I review the latest advances in color displays in major application markets and focus on those developments which result in enhanced functional color performance and improved image quality.

Introduction

Electronic color displays have become a part of everyday life. From television receivers to computer monitors to automobile dashboards and even aircraft cockpit instruments, the (once) ubiquitous color cathode ray tube (CRT) introduced modern color technology into our lives. With the advent of the shadow-mask color CRT around 1950 and the widespread introduction of color television in the late 1950s and 1960s, color display technology achieved important status. Color television continued to evolve and with it came heightened interest in other applications for electronic color imaging. However, despite the popularity and relative maturity of color television, most information display and graphics imaging applications were constrained to monochromatic display devices until the middle to late 1970s. The widespread use of color displays awaited the ready availability of computers and particularly the astonishingly rapid developments in microprocessors and personal computers which began in the late 1970s and early 1980s. Obviously, it was computer technology which provided the necessary processing power to enable color images to be generated and stored efficiently, but perhaps more importantly computers provided the means to effectively encode, manipulate and control color in electronic display systems. From this starting point for contemporary color imaging, and in only a scant twenty-five years, we have witnessed almost exponential growth in both the technology and application of color.

In the recent past, consumers and system developers had only very limited options when selecting a color display. Few technology alternatives to the color CRT existed. Although the venerable color CRT still commands a significant portion of the market, this device has undergone steady declines in market share as newer, more compact and more efficient display technologies have come to the forefront. Today we are confronted with a remarkable proliferation of display technologies. Figure 1 illustrates the range of currently available display technologies, most of which are capable of generating full-color images.[1] The hierarchical organization provided in Figure 1 conveniently segments display technology according to viewing mode (projection, direct-view and virtual) and whether the technology intrinsically generates light (emissive) or modules light from a separate external or internal source (non-emissive).

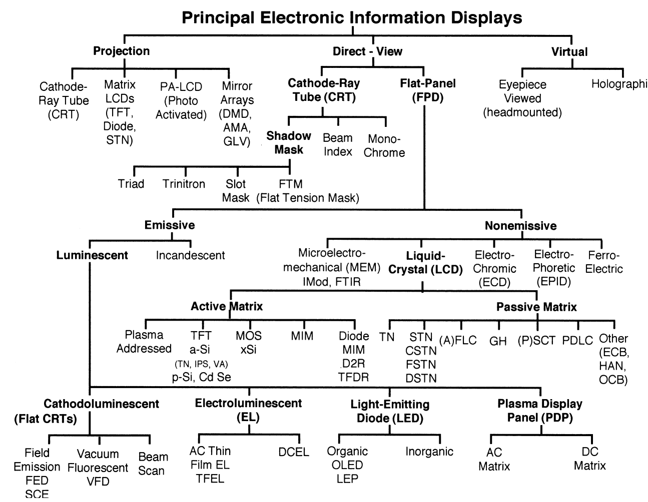

Figure 1. Hierarchical organization of currently available display technologies.

Regardless of the display technology employed, the common emphasis in virtually all application markets is on improved display image quality and lower display cost. Desired image quality improvements for all displays consist of enhancements in contrast, brightness and resolution. Although color displays are not required for all applications, color has become so ubiquitous that it has almost become a de facto requirement for consumers. Moreover, consumers are growing ever more knowledgeable about color, leading to expectations for improved color performance in the form of larger display color gamuts, enhanced color saturation and more accurate color rendering for all applications.

Currently the most active applications markets driving advances to enhance display color performance and improve image quality are at extreme ends of the market: large-area, flat-screen color displays for television (TV) and high-end computer monitors anchor one end of the market; and small, high-performance color displays for mobile devices such as cell phones, digital cameras and personal digital assistants (PDAs) define the other market extreme. Large-area display applications have been successfully addressed by a number of direct-view and projection display technologies. For the large-area direct-view technologies liquid crystal displays (LCDs) and plasma display panels (PDPs) dominate; although recent advances in organic light-emitting diodes (OLEDs), field-emitter displays (FEDs) and other flat cathodoluminescent devices make them potential contenders in future large-area markets. Projection displays for TV applications currently utilize image sources based on CRT, LCD and micro-electromechanical (MEMs) technologies such as the digital light processing (DLP) micro-mirror chip. Mobile displays are almost completely dominated by transmissive and transflective LCD technology; however, OLEDs, electrophoretic displays and some novel MEMs-based devices are poised to occupy several niche applications.

Advances in Display Color and Image Quality

The context provided above enables us to explore the most recent advances in display color performance and image quality. Because the application environments and performance requirements are so different, it is useful to consider large-area displays and mobile displays separately. Although these two display applications represent market extremes and thus may be expected to generate performance solutions tailored to their respective requirements, the advances resulting from these two applications will provide performance-enhancing solutions for all color displays.

Enhanced Color and Image Quality for Large Displays

The transition of TV from CRT-based receivers to more contemporary direct-view, flat-panel technologies and digital projection systems has renewed interest in improving TV image quality and color performance. This, of course, coincides with the widespread deployment of high-definition TV (HDTV). The various HDTV resolution standards provide progressive enhancements in picture resolution and detail over the broadcast standard adopted by the National Television Systems Committee (NTSC) in 1953, and numerous filtering and image processing methods have been applied to further enhance spatial and temporal image quality.[2] Each technology has provided evolutionary advances in materials and optics to reduce the black level, increase the display contrast ratio and provide higher peak luminance. All of the contemporary large-area display technologies have been striving to improve color performance by offering expanded color gamuts, optimized digital gamma functions, selectable white points and other enhancements. Of particular interest here are the ongoing efforts to expand the color gamut.

It has long been known than the color gamut based on the CRT phosphor primaries typically used for TV receivers and color computer monitors does not encompass the entire gamut of real-world colors.[3] Figure 2 shows the estimated gamut of real-world surface colors[4] compared to the gamuts of color primary standards for the original NTSC specification (obsolete)[2], the ITU-Rec.-709 standard which also specifies the sRGB primaries[2] and the primaries specified by the European Broadcast Union (EBU).[2] It is interesting to note that the original NTSC specification for color TV primaries, which are long obsolete due to market pressures for higher luminance in TV receivers,[2] provided substantially better chromaticity for the green and red primaries than found in today's TV receivers and computer monitors. This in turn provided for much better reproduction of important, naturally-occurring colors along the green-blue and green-red color axes than exists in current standards for display primaries. While the original NTSC specification was deficient for color reproduction along the red-blue axis, as are today's color standards, this region of color space is less critical for rendering of real-world colors as relatively few highly-saturated and naturally-occurring colors are found in this region. It is interesting that despite the fact that the NTSC color specification is long obsolete, it is now common practice to evaluate the efficacy of methods to expand the color gamut of TV and other displays by expressing the new gamut as a percentage of the NTSC gamut.

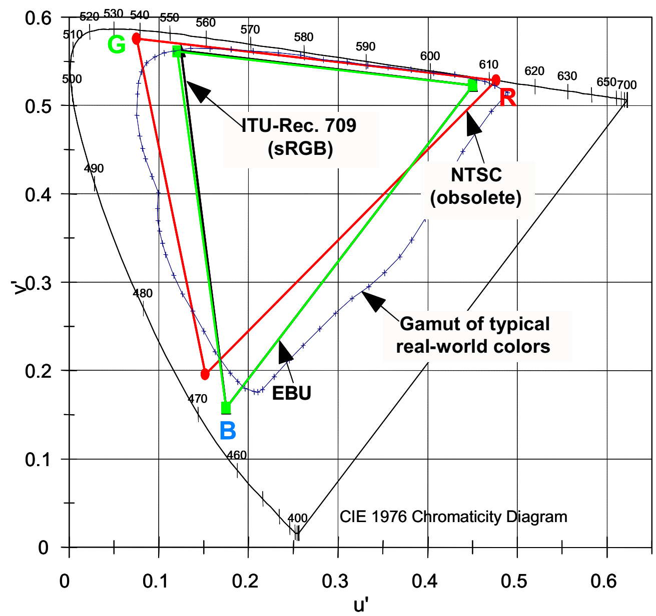

Figure 2. Color gamut of typical real-world colors as compared to original NTSC specification and ITU-Rec 709 and EBU color gamuts.

There are currently two major technology trends for expanding the display color gamut: the development and use of more saturated RGB primaries; and the development of displays with more than three primaries. In the case of improved RGB primaries, large-area emissive displays such as CRTs and PDPs must rely on the development of improved phosphors with narrower spectral emissions and/or the use of auxiliary color filters to limit the spectral passband. For direct-view color LCD panels and projection displays using either LCD or MEMs-based image sources, the preferred approach is to deploy narrow-band illumination sources such as LEDs or semiconductor laser sources. While the percentage of the NTSC color gamut occupied by the ITU-Rec. 709 or EBU primaries is approximately 75%, the coupling of LED backlights to large active-matrix LCD panels has already achieved color gamuts in excess of 105% of the NTSC specification.[5] Color television receivers which utilize LED illumination and possess expanded color gamuts are already commercially available from Sony and Samsung.[5] Moreover, compared to the fluorescent backlights commonly used for direct-view LCDs and the metal-halide arc lamps typically used in projection display systems, LED and laser illumination sources enable precisely selectable white points without sacrificing useable quantization levels and provide for more accurate, stable and spatially homogeneous control of color. It is noteworthy that the color performance advantages offered by improved RGB primaries require at most only simple remapping of the input data and therefore require only minimal additional processing resources.

The other approach to enhancing display color gamuts which is currently under active investigation is to develop displays with more than three primaries. To date prototype multi-primary displays with 4, 5 and 6 primary colors have been developed. Prototype multi-primary projection display systems have been developed with single DLP or liquid-crystal-on-silicon (LCoS) image sources and use temporal (field-sequential) color synthesis provided by a segmented color wheel.[6] Direct-view LCD prototypes have recently been developed using spatial color synthesis created with a six-primary pixel mosaic.[7] Novel combinations of temporally switched illuminants and multi-primary pixel mosaics have also been used to create wide-gamut direct-view LCDs with more than three display primaries.[8,9] All of these multi-primary (>3) approaches for achieving an expanded color gamut have demonstrated performance in excess of current ITU-Rec. 709 or EBU standards, and some have exceeded the gamut of the original NTSC color primary specification.

Expanding the display color gamut by utilizing more than the minimum set of three primaries required to exploit human trichromacy does not come without its costs. First, of course, are the inevitable reductions in spatial and/or temporal display resolution which occur in the various implementations of multi-primary spatial and temporal color synthesis. Second is the problem of on-screen metamerism and the additional processing resources needed for complex remapping of existing RGB input data into the new expanded set of primaries. The use of more than three primaries means that for many colors there is more than one way of reproducing them, and this metamerism requires additional signal processing algorithms.[10] Although the existing multi-primary prototypes have resulted in the development of a number of proprietary color mapping algorithms, it is unclear whether metamerism problems have been fully mitigated in any of these solutions. A recent approach to this problem now appears to offer a rigorous algorithmic solution.[11]

Enhanced Color and Image Quality for Mobile Displays

At the other extreme from large-area color displays, mobile applications have been dominated by technology solutions focusing on display visibility under diverse ambient illumination environments, compact and thin form factor, reduced power consumption and extended battery life. Given these requirements, it is not surprising that mobile displays are almost completely dominated by transflective and transmissive and LCD technology. However, as noted above, OLEDs, electrophoretic displays and some novel MEMs-based devices are under active development and appear poised to occupy several niche applications.

Most mobile display applications initially required only simple presentations of information such as alphanumerics and limited graphical icons. These requirements were satisfied with relatively simple, low-cost, monochrome passive-matrix displays; there was little need or market pressure for color. However, as mobile device bandwidths increased and internet usage became commonplace consumers demanded displays capable of higher information content. The rapidly expanding market for digital cameras created the need for small, high-performance mobile color displays for electronic viewfinders and on-board monitors for captured pictures. Finally, with the advent of picture phones and integrated digital cameras in cell phones and PDAs a new paradigm for high-resolution, full-color mobile displays evolved. The presentation of streaming video on mobile devices will further accentuate the demands for mobile display image quality.

Despite the shift toward mobile displays with higher image quality and full color, the core mobile display requirements for low-power consumption, small form factor and low cost remain. The need to reconcile these core mobile display requirements with high image quality and accurate, full-color reproduction presents great engineering challenges which are now only beginning to be addressed. As with the large-area displays, each technology has provided evolutionary advances in materials, optics and drive electronics to increase the display contrast ratio and provide higher peak luminance. For the dominant LCD technology these basic performance improvements along with enhanced color performance are being provided by: advances in white LED backlight technology (enhancement of both the spectral power distribution and luminous efficiency) and the development of small RGB backlights; optimization of color filter transmission spectra; and a shift away from transflective optical configurations to efficient transmissive optical designs.[12]

The color gamut of mobile color displays is compromised relative to the typical standards accepted for TV and computer monitors. This reduction in color performance is a direct consequence of engineering compromises required to satisfy the core mobile display requirements noted above. Figure 3 shows typical color gamuts of several mobile display technologies compared with the EBU color specification.

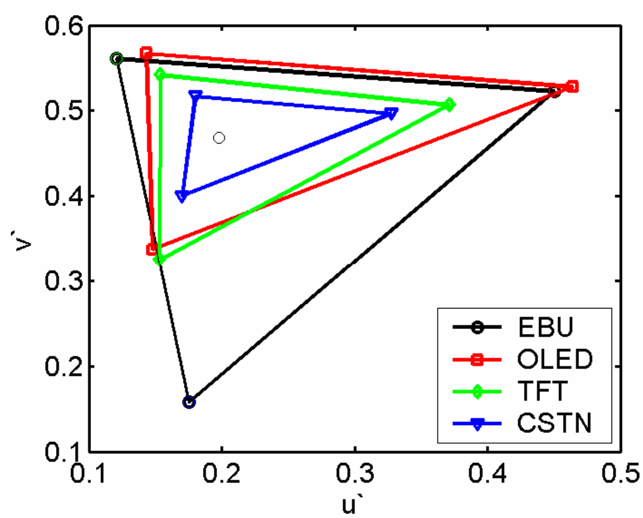

Figure 3. CIE 1976 chromaticity coordinates of the available color gamuts of typical mobile displays using TFT-LCD, OLED and STN-LCD technologies plotted with the EBU color specification as a reference.[13]

It has only recently been recognized that the increased requirements for mobile display image quality and color performance, combined with the requirements to display both still and video imagery, create the need for efficient color management and image processing techniques compatible with the processing resources of mobile devices.[13] Even rudimentary methods and algorithms for remapping input data (e.g. sRGB) into the color space of the mobile display can yield remarkable improvements in color accuracy and image quality.[13] Gamut mapping algorithms are also required to handle the inevitable out-of-gamut colors when going from a larger color space to a smaller one. A variety of image processing techniques such as contrast stretching, saturation enhancement and sharpening can all yield substantial improvements in mobile display image quality at relatively low system cost providing that the algorithms employed are well matched to the relatively limited on-board processing resources. Color management and image processing enhancements for mobile displays are currently active areas of investigation and engineering development.[14]

Hybrid Spatial-Temporal Color Synthesis

Image quality has been an important driving force behind the evolution of display technology. In all major market segments, the momentum toward higher display resolution and enhanced color quality is inescapable. This in turn has exposed the limitations of both spatial color synthesis and temporal color synthesis and raises the question as to whether either method for synthesizing color can alone fully satisfy the ever increasing demands on display image quality. Clearly, new approaches to color synthesis are needed to sustain the evolution of display technology.

Hybrid spatial-temporal color synthesis is a novel approach to the problem of display color synthesis which distributes the color synthesis function across both the spatial and temporal domains.[15] The approach is fundamental and can be adapted to most color display technologies, including direct-view matrix displays of both the non-emissive and emissive types, projection displays with matrix image sources and near-to-eye virtual displays. The general approach reduces the number of primary color sub-pixel elements from 3 to 2, arranges the 2 primary sub-pixel elements in a 2-D checkerboard mosaic and synthesizes the remaining 3rd primary color element by temporal synthesis.

Figure 4 shows one configuration of hybrid spatial-temporal color synthesis for a direct-view LCD and illustrates the general principles of the method which must be adapted to specific applications. In this configuration an illumination source switchable between yellow (Y) and blue (B) spectral power distributions is combined with an LCD panel and pixel mosaic consisting of a checkerboard pattern of magenta (M) and cyan (C) color filters. The sources of illumination may be combinations of LEDs, CCF fluorescent lamps, laser diodes or any other potential source with suitable spectral, temporal and intensity characteristics. When the Y illuminant is activated during one temporal field the display output consists of a checkerboard pattern of red (R) and green (G) sub-pixels. Activation of the B illuminant during an adjacent temporal field yields a display output of homogeneous B sub-pixels. The temporal combination of the two fields yields a full-color display. Since the homogeneous B field provides twice the space-average amount of B required to achieve white balance, light throughput efficiency of the system may be enhanced by doubling the relative duration of the R/G fields. While there are many possible ways to partition the spatial and temporal components, this configuration isolates the short-wavelength contribution to the temporal domain and thus capitalizes on the unique structure and attributes of the human visual system color channels.[15]

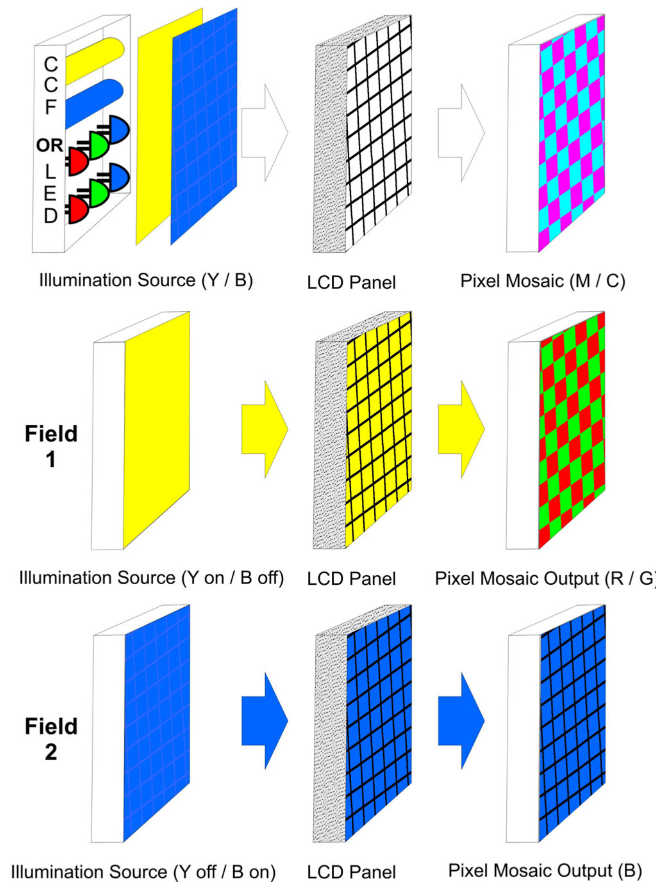

Figure 4. One configuration of hybrid spatial-temporal color synthesis for transmissive LCD displays which provides enhanced visual image quality.

This new method offers significantly enhanced effective resolution and addressability as well as very low fixed-pattern noise relative to displays using spatial color synthesis alone. Dramatic reductions in color field rate, minimization of color break-up and improved light efficiency relative to displays using temporal color synthesis can also be realized with hybrid spatial-temporal color processing. Moreover, the method provides many degrees of freedom for selecting combinations of temporally switched illuminants and color filter mosaics to achieve different display performance objectives such as extending the display color gamut or enhancing the luminous efficiency of the display. Researchers from Philips Laboratories have recently prototyped and demonstrated displays based on hybrid spatial-temporal color synthesis which achieve an impressive expansion of the display color gamut and significant improvements in luminous efficiency.[16]

The Future of Color Displays: Evolution and Revolution

Color display technology and applications continue to advance at a steady pace. Most of the advances are evolutionary and driven by improvements to existing technology. Incremental advances in materials, optics, drive electronics and processing algorithms have in turn enabled incremental improvements in display image quality. The development of sophisticated modeling and analysis tools have greatly facilitated the optimization of existing technologies.[17]

An important issue for the future of color displays is whether such incremental improvements in technology will provide the image quality to satisfy the rapidly growing demands of color imaging. Perhaps revolutionary changes or paradigm shifts will be required to meet tomorrow's imaging requirements. One recent paradigm shift is the development of multi-primary color displays. This approach offers the potential of dramatically larger display color gamuts and, when coupled with multi-channel color image capture devices, could result in major changes in the nature of color imaging. Hybrid spatial-temporal color synthesis is another recent development with the potential for revolutionary change in color display image quality.

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Louis D. Silverstein received the Ph.D. in psychophysics and vision science from the University of Florida in 1977. He has held research positions at several major U.S. corporations. In 1990 he founded VCD Sciences, Inc., a technical consulting organization involved in R&D in applied vision, color science and display technology. He is a member of numerous technical societies and is a Fellow of the SID. Dr. Silverstein is the author of over 120 journal articles, book chapters, technical papers, and technical reports and has been awarded thirty patents on advanced display technology.