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A high resolution, high dynamic range display for vision research

James Ferwerda, Stefan Luka
Munsell Color Science Laboratory, Chester F. Carlson Center for Imaging Science,
Rochester Institute of Technology

Electronic display systems have been a boon to vision researchers for their flexibility as stimulus generators. However conventional displays only produce moderate luminance levels and limited contrast ranges. This constrains their utility as tools for exploring visual response over the vast levels and ranges we experience in the real world. Fortunately high dynamic range (HDR) displays are being developed that can produce luminance levels and contrasts on the order of those encountered in real world scenes. Typically, these displays use a LCD front panel with a spatially modulated backlight produced by a digital projector or LED array. One consequence of this design is that the backlight only shows a low frequency image, which limits the range of spatial frequencies that can be produced at high luminance contrasts. This reduces the value of these displays as visual stimulus generators. To address this problem we have developed a high resolution, high dynamic range display system for vision research that is capable of producing high luminance contrasts across a broad range of spatial frequencies. The display's front panel consists of a 30" Apple LCD monitor with 2560x1600 addressable pixels. The backlight image is produced by a tiled array of DLP projectors that we have corrected geometrically and colorimetrically using custom camera-based calibration software. The display is capable of producing spatial frequencies up to 12 cycles/degree (24" viewing) at luminance contrasts up to 40,000:1. We are using the display for material perception studies, where high intensity specular reflections are important, and for low vision research, where deficits often appear at extreme luminance contrasts. This display represents a useful new tool for vision research that can be constructed using commodity display hardware and standard image tiling methods.

A high resolution, high dynamic range display system for vision research

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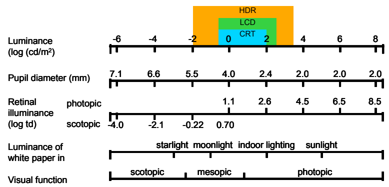
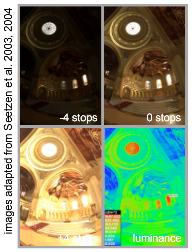
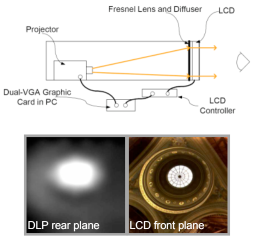
- **Background / motivation:**
  - the changes in luminance we experience are vast



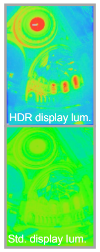
  - mean level: ~100,000,000:1 (sunlight to starlight)
  - dynamic range: >10,000:1 (highlights to shadows)
  - vision is not equally good under all conditions
    - variations in contrast sensitivity, acuity, color, motion, stereo, …
    - performance losses increase with aging, disease
  - currently hard to study the effects of large luminance changes on real-world visual performance in lab/clinic
    - standard display systems limited
    - 100 – 400 cd/m² typical max. luminance
    - 30:1 – 100:1 usable dynamic range
- **High dynamic range (HDR) display (Sunnybrook/Dolby):**
  - capable of significantly higher luminance, dynamic range
  - dual plane design
    - transparent LCD front plane with DLP backlight
    - plane values multiply to produce HDR output



HDR input image



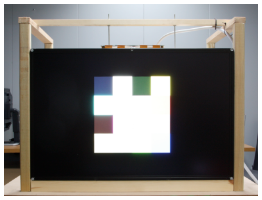
image/display mapping



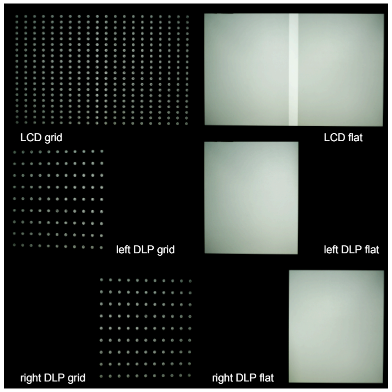
display output

  - limitations
    - brightness, resolution limited by rear plane
    - cost proportional
  - new approach
    - HDR display with tiled commodity projectors

- **Alignment of components / Geometric registration:**
  - projectors must be aligned with front panel, fresnel lens
  - two projectors can be rotated 180° to each other to share a common optical axis with fresnel lens
  - basic alignment sufficient, no fine mechanical adjustment required
  - coordinate mapping needed between projector and front panel pixels to produce registered images



  - camera-based technique performs automatic registration to establish subpixel mapping and measure spatial falloff



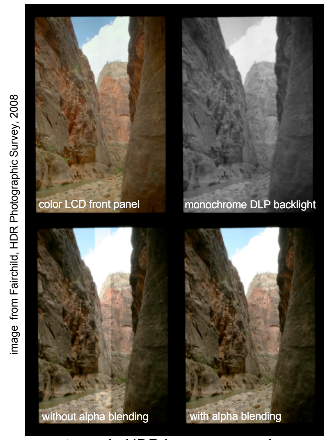
  - morphological targets used to encode reference points in grid

- **Colorimetric characterization:**
  - colorimetric model is used to predict XYZ output from device RGB (front panel) and A (backlight) input

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \left(\begin{bmatrix} X_r & X_g & X_b \\ Y_r & Y_g & Y_b \\ Z_r & Z_g & Z_b \end{bmatrix} \times \begin{bmatrix} R \\ G \\ B \end{bmatrix} + \begin{bmatrix} X_k \\ Y_k \\ Z_k \end{bmatrix} \right) \cdot \left(A(1 - A_k) + A_k \right)$$

  - RGB primaries and black level are measured for each LCD/DLP pairing
  - OETF measured for LCD and DLPs to linearize response
  - 760 cd/m² peak lum., 41,500:1 dynamic range

- **Image processing:**
  - bright seams occur where projectors overlap
    - alpha blending needed to eliminate seams
    - geometric registration used to identify overlapping regions and create alpha masks
  - HDR image split across image planes for display
    - front panel produces a color image, backlight produces a spatially filtered monochrome image
    - new splitting strategy optimizes gamut utilization, improves reproduction of deep, dark colors



stages in HDR image processing

equation for backlight image (A)

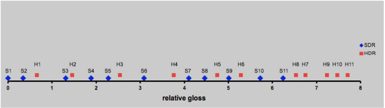
$$A = \frac{t}{\sqrt{t} \cdot (1 - s) + s}$$

s, relative distance between neutral axis and gamut edge

t, relative distance between gamut upper limit and lower limit

RGB image is calculated from A and inverse colorimetric model

- **Software environment:**
  - display operates within Matlab, utilizes standard PsychToolbox functions
  - HDR images can be preprocessed for fast presentation
- **Research applications:**
  - visual performance under HDR conditions
  - effect of image dynamic range on perceived surface gloss



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