A low-cost, color-calibrated high dynamic range display

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High dynamic range (HDR) displays are enabling new advances in visual psychophysics, but commercial HDR displays are both expensive, and difficult to calibrate colorimetrically. Homebrew HDR displays incorporating LCD panels and digital projectors are relatively inexpensive and can be calibrated, but building such displays requires sophisticated technical skills. We have developed a low-cost, color-calibrated HDR display for vision research that can be constructed and used by researchers without the need for specialized equipment or advanced engineering abilities. Inspired by the work of Bimber et al., this print-based HDR display incorporates an inkjet printer, a digital video projector and a digital camera. To display an HDR image, the image is first processed through the iCAM06 color appearance model to produce a standard dynamic range (SDR) image that is sent to the printer. The digital video projector is then roughly positioned so its image field covers the print. Custom camera-based structured-light image registration software then automatically aligns the projected and printed images. A separate camera-based color calibration module then measures the print colors and determines the values to send to the projector to achieve the best possible reproduction of the original HDR image. This iCAM-based approach to HDR color reproduction goes substantially beyond prior work in terms of its colorimetric accuracy. With respect to intensity and dynamic range, because the print area is substantially smaller than a projector's typical field size, the maximum intensity in the combined image can be quite high, and the current display has a peak luminance over 2000 cd/m^2 with a dynamic range of 20,000:1. While the print-based nature of this display does limit its usefulness for interactive studies, its low-cost, do-it-yourself design, and ability to be calibrated should make a valuable addition to the vision researcher's laboratory.

A low-cost, color-calibrated, reflective high dynamic range display

MCSL

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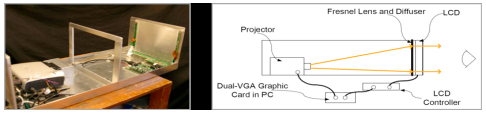
Abstract: We have developed a low-cost, color-calibrated HDR display that can be constructed and used by vision researchers without the need for specialized equipment or advanced engineering abilities. Inspired by the work of Bimber et al. 2008, this print-based HDR display incorporates an inkjet printer, a digital video projector and a digital camera. To drive the display, an HDR image is first processed through the iCAM06 image appearance model to produce a standard dynamic range (SDR) image that is sent to the printer. The digital video projector is then roughly positioned so its image field covers the print. Custom camera-based structured-light image registration software automatically aligns the projector and print fields. A color calibration module measures the print colors and determines the values to send to the projector to achieve the best possible reproduction of the original HDR image. This iCAM06-based approach to HDR color reproduction goes substantially beyond prior work in terms of its colorimetric accuracy. Our current display that uses a table-top DLP projector and commodity ink-jet printer has a peak luminance of ~2000 cd/m^2 with a dynamic range of ~20,000:1. While the print-based nature of this display does limit its usefulness for interactive studies, its low-cost, do-it-yourself design, and its ability to produce calibrated output should make it a valuable addition to the vision researcher's laboratory.

- **Background / motivation:**

Images from HDR Photographic Survey, Mark Fairchild, 2008.

  - images taken at different exposure times can be merged into a single HDR image
    - 10,000 to 1,000,000:1 dynamic range
  - impossible to view HDR images on standard displays
    - typically 30:1 – 100:1 usable dynamic range

- **High dynamic range (HDR) display (Seetzen et al. 2003):**
  - dual image plane design
    - transparent LCD front plane with DLP backlight
    - image values multiply to produce HDR output



Images from Seetzen et al. 2003.

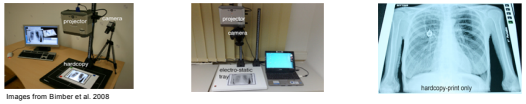
  - limitations
    - cost, not commercially available
    - "black-box" image processing not suitable for research

- **MCSL HDR display (Luka and Ferwerda, 2008):**
  - HDR display with tiled commodity projectors

Images from Luka et al., 2009.

  - ~760 cd/m^2 peak lum., ~41,500:1 dynamic range
  - calibrated output, integrated with PsychToolbox
  - limitation: construction requires considerable technical skill

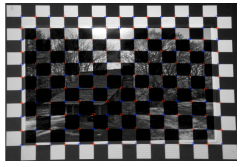
- **A reflective HDR display (Bimber et al. 2008):**



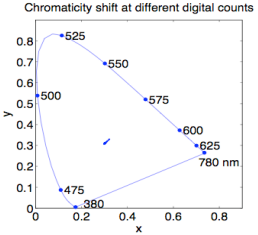
Images from Bimber et al. 2008

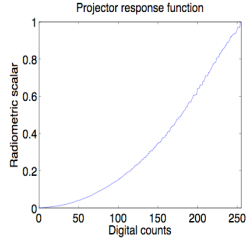
  - built from low cost, off-the-shelf components (camera, projector, printer, laptop)
  - flexible construction, alignment methods
  - limitation: "square-root" HDR image splitting algorithm used is not colorimetrically accurate

- **New Approach:**
  - calibrated print-based HDR display
  - new appearance-based HDR image splitting algorithm
- **Geometric registration:**
  - custom structured light (checkerboard) image registration software measures misalignment of projector and print
  - affine transform is calculated to register the images

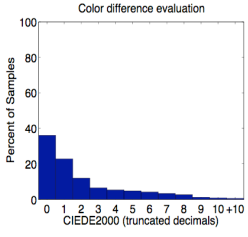


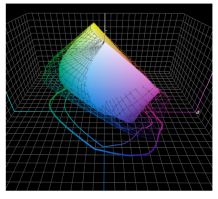
- **Colorimetric characterization (projector):**





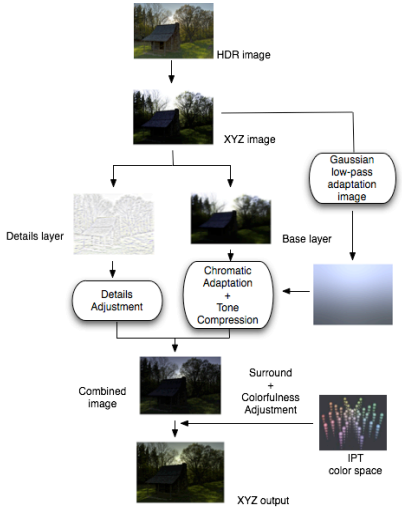
  - luminance/color stability of DLP projector is measured
  - output is linearized through calculated LUTs
- **Colorimetric characterization (printer):**



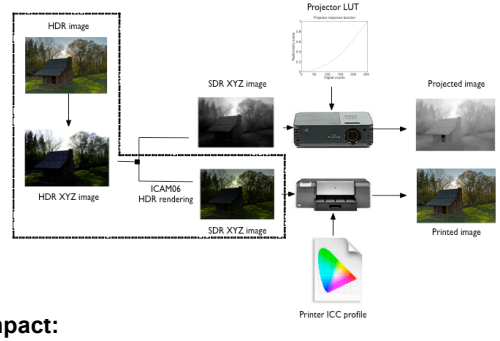


  - color output managed through custom ICC profile
  - paper type affects color gamut volume
    - mesh: HP satin matte photo; solid: HP canvas
- **Display performance:**
  - ~2000 cd/m^2 peak lum., ~20,000:1 dynamic range

- **New HDR image splitting algorithm:**



  - algorithm based on the iCAM06 image appearance model
  - HDR image is split by a bilateral filter into base and details layers
  - low pass version of the image is used to transform the base layer to account for luminance and color adaptation
  - adapted base layer is then recombined with the details layer
  - combined image is then processed through the IPT opponent color space to model luminance related colorfulness and surround effects
  - resulting linear RGBs are then corrected by projector and printer LUTs for output



- **Impact:**
  - low-cost, off-the-shelf, DIY HDR display
  - color calibrated output suitable for image perception/quality research
  - integrated with PsychToolbox
  - additional applications: radiology, astronomy, virtual museums

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