Color correction for tone mapping

EUROGRAPHICS 2009,
Vol. 28, No. 2, 2009
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Abstract

◆ Tone mapping algorithms
  – Offer sophisticated methods for mapping HDR to LDR
  – Changes in color appearance

◆ Measurement of change after tone mapping
  – Indication of relation between contrast compression and color saturation correction

◆ Proposal of color correction formulas
  – Available existing tone mapping algorithms
Introduction

◆ Tone mapping algorithms
  – Often cause changes in color appearance
  – Luminance compression
    • Darker tones to appear brighter
    • Distort contrast relationships

Fig. 1. An original image compared with three images after contrast compression.
Object of this work

- Quantify and model correction in color saturation
- Distrust predictions of existing appearance models
  - Instead conduct subjective appearance matching
    - Measure necessary color correction
- Find new chrominance values
  - Tone mapped image closely matches appearance of image with no tone modification
Related work

◆ Color reproduction
  – Well studied in context of gamut mapping
  – Gamut mapping
    • Modify both luminance and chrominance to preserve color appearance
    • Much smaller contrast compression than tone mapping
    • Operate on display-referred images
  – Proposed method
    • Only modify chrominance
      – Tone mapping modify luminance
    • Operate on scene-referred images
Color appearance studies

- Apparent colorfulness of uniform color patches
  - Vary with luminance, image size, and color of surround
  - Hunt effect
- Apparent lightness of color patches
  - Depend on chromacity
  - Helmholtz & Kohlrausch effect
- Apparent hue
  - Depend on luminance
  - Abney effect
- Perceived contrast of images
  - Decrease with reduced chroma
  - Sigmoidal relation
Color reproduction in tone mapping

- Focus on preserving color appearance of real-world scene

- Pattanaik et al.
  - Introduce complex model of human color vision
  - Introduce opponent color processing
  - Gain control for both luminance and contrast signals

- Later work
  - Focus on aspects of temporal adaptation
    - Use photoreceptor model instead of luminance gain control
  - Employ simplified appearance model based on Hunt’s model
Color appearance model

- iCAM color appearance model
  - Achieve contrast compression
    - Applying spatially varying power function to three color channels in LMS color space
- iCAM06 color appearance model
  - Replace power function with photoreceptor response model
  - Consider separately scotopic and photopic signals
  - Account for perceived contrast change with adapting luminance level and with surround luminance
  - Compensate for increased colorfulness with luminance
– Akyuz and Reinhard
  • Propose color processing framework
    – Adapt to any tone mapping that preserves ratios between color channels
  • Use forward and then backward CIECAM02 model
– Mentioned tone mapping operators
  • Account for color differences
    – Result of different luminance and chromatic adaptation between real-world scene and display viewing conditions
  • No considered change in color appearance
Color correction in tone mapping

◆ Common approach to color treatment
  – Preserving color ratios

\[ C_{out} = \frac{C_{in}}{L_{in}} \cdot L_{out} \]  

where \( C \) is one of RGB color channels, 
\( L \) is pixel luminance, and
\( in/out \) is pixels before and after tone mapping.

• Stronger contrast compression in tone mapping
  – Over-saturated result image
◆ Ad-hoc formula

\[ C_{out} = \left( \frac{C_{in}}{L_{in}} \right)^s L_{out} \]  \hspace{1cm} (2)

where \( s \) is color saturation control factor.

– Drawback of equation

• Change resulting luminance for \( S \neq 1 \) and for colors different from gray

\[ k_R R_{out} + k_G G_{out} + k_B B_{out} \neq L_{out} \]

where \( k_{R,G,B} \) are linear factors to compute luminance for given color space.
Introduction of another color correction

\[ C_{out} = \left( 1 - \frac{C_{in}}{L_{in}} \right)^2 \frac{L_{out}}{s + 1} \]

- Difference between equation 2 and 3
  - Change in \( S \) from Equation 2
    - Modification both chroma and lightness of colors
  - Change in \( S \) from Equation 3
    - Prevent lightness, but lead to stronger hue shift

Fig. 2. CIECAM02 prediction of hue, chroma, and lightness for the non-linear (a) and luminance preserving (b) color correction formulas.
Another approach to color treatment

– Apply same tone mapping curve to all color channels
  • Form of tone curve
    \[ L_{out} = \left( L_{in} b \right)^c \]  
    where \( b \) is brightness adjustment that normalizes for maximum display brightness.
  • Another arbitrary tone-curve
    – Apply color correction factor \( s \) of Equation 2
      » Not equivalent to \( s = c \)
      » Results are very close
  • In case of local tone mapping operators
    – All channels usually cannot be modified simultaneously
    – Rely on color transfer formulas, such as Eq. 2 or 3
Equations 2 and 3

- Convenient way of correcting colors in RGB
- Manual adjustment of parameter $s$

Object

- Estimation of color correction parameter $s$ given luminance-specific tone-curve
Experiment 1: color matching for tone mapping

- Practice of subjective study
  - How much color correction is required to compensate for contrast compression?

- Participants of experiment
  - Split into two parts to test
    - Test group for non-linear Equation 2
    - Test group for luminance preserving Equation 3
◆ Stimuli

– 8 natural images in experiment

Fig. 3. HDR and LDR images used in the experiments.
- Image processing
  - Use Eq. 4 for contrast compression
    - Contrast factor $c$ varied from 0.1 to 1.6
  - Use Eq. 2 and 3 for Color correction
    - Color saturation factor $s$ were adjusted by participant
- Reduce luminance of input image
  - Use 33% of display peak luminance
  - Avoid out-of-gamut

Fig. 4. Tone mapping and color correction used in the experiments.
◆ Experimental procedure
  – Change color correction factor $s$ by participants
  – Matching colorfulness
    • Average of both left and right image

![Fig. 6. Screenshot from the experiment.](image-url)
● Results
  
  – Averaged results for both color correction formulas
    • Moderate contrast correction for small contrast
  
  – Relation between $c$ and $s$
    • Approximate with power function $s(c) = c^{k_3}$
    • Approximate with $s(c) = \frac{(1 + k_1) c^{k_2}}{1 + k_1 c^{k_2}}$ (5)

Fig. 5. Result of matching colors between image with altered contrast and an original image.
Color appearance models and color correction

- Color appearance models
  - Predict non-linearity in visual system
  - Provide set of perceptual attribute predictors
    - Colorfulness, chroma, and saturation

- Object of this experiment
  - Find which perceptual attribute should be preserved after contrast compression
    - Six basic colors of different hue, saturation, and lightness
      - Compress contrast $c \in [0, 2]$ with respect to reference white
      - Color correction factor $s$ determined by Eq. 5
    - Result colors
      - Transform to space of perceptual attribute predictors
– Result colors of CIECAM02 space
  • CIECAM02 saturation
    – Most consistent across contrast variation
  • Relation between the saturation and contrast compression
    – Non-linear relation

Fig. 7. CIECAM02 prediction (hue, saturation, and lightness) for color change.
Limitations of color correction in RGB space
- Either preserve lightness but distort hue, or preserve hue but distort lightness

Color correction in space of perceptual attributes
- CIELAB or CIELUV color space
- Simpler color correction
- Resulting images
  - Better match to originals
◆ Framework for color correction in CIELAB

– Luminance of original image
  • Tone mapping by Eq. (4)

– Chroma of original image
  • Correct by factor $s_{LAB}$

– Combine lightness and corrected chroma

Fig. 8. Colors correction in the CIELAB color space.
◆ Result of experiment
  – Small contrast modification (0.6 < c < 1.6)
    • Color correction
      – Almost unnecessary (s_{LAB} \approx 1)

Fig. 9. Result of matching image colors using color correction in CIELAB color space.
Illustration of $s_{LAB}$ color correction in CIECAM02

- Color correction in CIELAB
  - Better preserve hue and lightness

Fig. 10. CIECAM02 prediction for color correction in CIELAB space.
Are color appearance models suitable for tone mapping?

◆ CIELAB chroma predictor
  – Better preserve color appearance after contrast compression
    • Seem to be alternative to color correction in RGB color space
  – Limitation for HDR scenes
    • Estimation problem of reference white color
Different selection of reference white

- Lead to completely different colors
- Automatic estimation of reference white
  - Difficult problem
  - Some methods exist
    - Lead to unreliable estimation

Fig. 11. High dynamic range image before and after tone mapping while preserving CIELAB chroma.
Application in tone mapping

◆ This subjective study
  – Demonstrate relation between contrast compression and color correction
  – Applicable to global and local tone mapping

Fig. 12. Results of four color correction methods for contrast compression (top) and enhancement (bottom).
Bilateral tone mapping
- Uniformly reduce contrast of base layer while detail preserving
- Produce good result, but over-saturated colors
- Using proposed method
  - Fix over-saturated colors

Fig. 13. The result of the “bilateral” tone mapping with strong contrast compression, original algorithm compared to the algorithm with color correction.
Proposed color correction formulas

- Apply to simplified operator with contrast factor $c$
- Apply to any tone mapping function
  - Contrast factor
    - Approximate by slope of tone curve on log-log plot in logarithmic space

$$\hat{L}_{out} := tmo\left( L_{in} \right)$$
$$c\left( L_{in} \right) = \frac{d}{d\hat{L}} tmo\left( \hat{L}_{in} \right)$$

where $\hat{L} = \log_{10}(L)$
Display adaptive tone mapping
- Employ Eq. (2) to compensate for color difference
  - Manually adjust color correction factor \( s \)
- Using proposed method
  - Automatically readjust \( s \)

\[
C_{out} = \left( \frac{C_{in}}{L_{in}} \right)^{s} L_{out}
\]

Fig. 14. The result of the “display adaptive” tone mapping.
Proposed method

- Consideration of only global tone mapping
  - Affect only low frequencies

- Pilot study
  - Investigate effect of local operation, unsharp masking, and colorfulness images
  - Main component of local tone mapping operators
    - Sharpening
    - Proposed color correction
      » Valid method for local tone mapping operators

Fig. 15. Enhancement and compression of details has little effect on colorfulness as compared to global contrast modification.
Conclusions and future work

◆ Tone mapping operator
  – Distort image due to tone and color reproduction

◆ Proposal method
  – Predict desirable color correction
  – Simple and computationally inexpensive formulas
  – Applicable for global and local tone mapping
  – Exist problem of reference white estimation

◆ Future work
  – Isolate set of factors that influence colorfulness after local tone mapping operations