Paramer Mismatch-Based Spectral Gamut Mapping

*IEEE Transactions on Image Processing, Vol. 20, No. 6, 2011*

Philipp Urban and Roy S. Berns

Presented by Ran Shu

School of Electrical Engineering and Computer Science
Kyungpook National Univ.
Abstract

◆ Spectral agreement
  – Achieving illuminant-invariant visual match

◆ Spectral gamut of typical printing systems
  – Small subset of all natural reflectances

◆ Out-of-gamut reflectances
  – Mapping into gamut of printer
    • Minimizing perceived error between original and reproduction for more than one illuminant
Proposing separation method for spectral gamut mapping

- Sequence of hierarchical mapping in color space
  - Most important illuminant
    - Traditional colorimetric gamut mapping
  - Any additional illuminants
    - Mapping onto pixel-dependent parameter mismatch gamuts
      » Preserving visual equivalence of previous transformation
- For second and subsequent illuminants
  - Hue shifts and chroma gains cannot be always avoided
- Order of illuminants
  - Large impact on final reproduction
Ability of printing devices to reproduce colors

- Limiting by colorimetric printer gamut
  - Set of all colors physically reproducible by device
- Nonreproducible colors
  - Transforming into printer gamut
    - Using gamut mapping algorithms
      » Minimizing perceptual difference between original and reproduction
- New printing systems
  - Utilizing multiple colorants in additional to traditional CMYK-set
• CMYKRGB printers
  – Optimizing to increase gamut size
    » Reducing adverse effects of gamut mapping
• Much higher colorimetric redundancy
  – Reproduction of same color using metameric spectra
    » Producing by different colorant combinations
• Colorimetric separation algorithms
  – Selecting one of colorant combinations
    » Utilizing additional application-dependent goals
      » Minimizing ink coverage or grain
– Traditional separation algorithms
  • Match between hard copy and original
    – Under one illuminant
    – Specific observer
  • Observer or illuminant changing match does not persist
    – Overcoming by new separation algorithms
      » Utilizing colorimetric redundancies
      » Choosing colorant combination

– Ultimate goal of separation
  • Perfect spectral agreement between original and reproduction
– Another possible goal for separation
  • Reproduction matching with original
    – Under one illuminant
  • Reproduction staying color constant
    – Under other illuminants
– Gamut mapping challenge of spectral-based reproduction
  • Different comparing to colorimetric reproduction
    – Using printing systems with many colorants
      » Spectral gamut in general dimensions smaller than space of nature reflectances
Arbitrary spectral reflectance is not within the spectral gamut of printer

- Indicating whether a reflectance is part of spectral gamut
  - Utilizing spectral printer model
    » Predicting function
    » From control value space to spectral space
    » Spectral gamut is only implicitly given as image of whole control value space

- Characterization and access to colorimetric gamut boundaries
◆ Developing intent of spectral gamut mapping
  - Distance measure between given and printable reflectance
    • Minimizing in gamut mapping transformation
  - Metric in spectral space
    • Using for spectral gamut mapping
      - Lacking of correlation to visual distances
        » Especially for dark colors
        » Large color differences
– Advantage comparing to traditional reproduction
  • Spectral reproduction
    – For one illuminant
      » As visually correct as colorimetric reproduction
    – Superior other illuminants
  • Previous approach
    – Combing mapping within perceptual color space
      » One illuminant and spectral mapping within corresponding
    – Performing spectral gamut mapping exclusively in spaces relating to human color vision
      » Using metamer mismatch gamuts
◆ Proposing method
  – Using parameter mismatch gamut
    • Utilizing color quantization of human visual system
      – Increasing spectral variability for particular mapping
Describing the gamut mapping framework

◆ Terminology
  – CIE XYZ tristimulus
    • Calculating from spectral stimulus
      \[ X(I,r) = \frac{100}{\int_{\Lambda} Y(\lambda)I(\lambda)d\lambda} \begin{bmatrix} x(\lambda) \\ y(\lambda) \\ z(\lambda) \end{bmatrix} I(\lambda)r(\lambda)d\lambda \]  
      where \( \Lambda = [380\text{nm}, 730\text{nm}] \) is the visible wavelength range and \( x, y, z \) are the CIE color matching functions (CMFs), which can be either 2 or 10 degree
  – Typical objective of gamut mapping
    • Minimizing perceptual difference
      – Between original and gamut mapped image
• Mapping is performed within color spaces
  – Forming by perceptual correlates
    » Lightness and chroma and hue
• Frequently using color spaces
  – Hue corrected CIELAB color space
  – IPT color space
• Comparing to CIELAB color space
  – Beneficial properties for gamut mapping
    » Hue linearity
    » Closer to perceptual uniformity
• Proposing transformation from CIELAB into CIELAB
  – $L$: CIELAB $\rightarrow$ CIELAB
  – Inverse $L^{-1}$: CIELAB $\rightarrow$ CIELAB
– Proposing color difference threshold
  • Separating parameters from nonparameters
  • Using fraction of just noticeable distance (JND)
    \[
    \Delta E \left[ L(\text{X}(I,r_1)), L(\text{X}(I,r_2)) \right] \leq \frac{D_{JND}}{2}
    \] (2)
    where \(D_{JND}\) is the JND and \(\Delta E\) might be any color difference formula
  • Set of all parameters for given CIELAB value \(c\)
    \[
    \beta(I,c) = \left\{ r(\lambda) \left| \Delta E \left[ L(\text{X}(I,r)), c \right] \leq \frac{D_{JND}}{2} \right. \right\}
    \] (3)
  • Metameric printer gamut
    – Representation of spectral printer gamut \(\mathcal{G}\)
      » Within perceptual correlate-based color space for specific illuminant \(I\)
    – Using CIELAB color space
      \[
      G(I,\mathcal{G}) = L(\text{X}(I,\mathcal{G}))
      \] (4)
Methodology

- Goal of parameter mismatch-based spectral gamut mapping
  - Replacing nonreproducible spectra
    - Using reproducible spectra based upon colorimetric criteria
      » For multiple illuminants

- Only performing within color spaces based upon perceptual correlates
  - Distances agreeing well with perceptual color differences
    - Instead of mapping spectral image into spectral printer gamut
      » Using single objective function
        » Mapping performing sequentially

- Method of mapping
  - First mapping transforming spectral image
    - Using most important illuminant $I_1$
– Reducing degrees of freedom for subsequent mapping

• Mappings for next illuminants
  – Depending upon results of previous mappings

– Step 1

• Rendering spectral image \( R = \{ r_{x,y}(\lambda) \mid x = 1, \ldots, N, y = 1, \ldots, M \} \)
  – For all considered illuminants \( I_1(\lambda), \ldots, I_n(\lambda) \)
  – Transforming each pixel reflectance into 3 X n dimensional matrix

\[
\begin{align*}
  r_{x,y}(\lambda) &\rightarrow \left\{ \begin{array}{c}
  L\left( X\left( I_1, r_{x,y} \right) \right), \ldots, L\left( X\left( I_n, r_{x,y} \right) \right) \\
  = l_{x,y}(1) \quad \text{=} l_{x,y}(n)
  \end{array} \right. \\
  = \left( l_{x,y}(1), \ldots, l_{x,y}(n) \right) &\in \text{CIELAB}^n
\end{align*}
\] (5)

– Combination of n different CIELAB images

\[
L_k = \{ l_{x,y}(k) \mid x = 1, \ldots, N, y = 1, \ldots, M \}
\] (6)

where \( k = 1, \ldots, n \) and \( l_{x,y}(k) \) is defined in (5)
– Step 2

• Most important illuminant $I_1$
  – Achieving color reproduction similar to high quality metameric reproduction
  – Using traditional metameric gamut mapping

\[
\Gamma_{\text{Trad}} [I_1, \mathcal{G}] : L_1 \rightarrow \hat{L}_1
\]  

where the illuminant $I_1$ and the spectral printer gamut $\mathcal{G}$ are parameters of this transformation

– General objective of traditional gamut mapping
  » Representation of image $\hat{L}_1$ within metameric printer gamut
  » Minimizing perceptual difference to original image $L_1$
– Step 3

• Adjusting reproduction to second illuminant $I_2$
  – Without noticeably changing results for $I_1$

• Gamut-mapped CIELAB color under $I_2$ with results of $I_1$
  – May not reproducing by in-gamut spaces

• Gamut mapping transformation under second illuminant
  – Illuminant $I_1$ reducing degrees of freedom
  – Pixel dependent paramer mismatch gamut

$$P(\hat{I}_2, I_1, \mathcal{G}, \hat{i}_{x,y}(1)) = L\left(X(I_2, \beta(I_1, \hat{i}_{x,y}(1)) \cap \mathcal{G})\right) \quad (8)$$

– Simply paramer mismatch gamut

$$\Gamma_{Para}[I_2, I_1, \mathcal{G}, \hat{L}] : L_2 \rightarrow \hat{L}_2 \quad (9)$$

where the illuminants $I_2, I_1$, the spectral gamut $\mathcal{G}$ and
the already gamut mapped image $\hat{L}$ are parameters of the transformation,
$L_2$ is the original CIELAB image and $\hat{L}_2$ is the image within the pixel dependent
paramer mismatch gamuts
- Each pixel \( \hat{i}_{x,y}(2) \)

\[
\hat{i}_{x,y}(2) \in P\left( I_2, I_1, 2\hat{i}_{x,y}(1) \right)
\]  \( (10) \)

- Performing in color space with metric
  - Correlating with color difference perception
  - Color space designing perceptual correlates easily accessed
    » Preserving hue angle

- Presenting three parameter mismatch-based transformations
  - Deriving from color difference formulas

\[
\hat{i}_{x,y}(2) = \arg\left( \min_{z \in P^2} \Delta E_a^* \left( z, l_{x,y}(2) \right) \right) 
\]  \( (11) \)

\[
\hat{i}_{x,y}(2) = \arg\left( \min_{z \in P^2} \Delta E_{94(2:1:1)}^* \left( z, l_{x,y}(2) \right) \right) 
\]  \( (12) \)

\[
\hat{i}_{x,y}(2) = \arg\left( \min_{z \in P^2} \Delta E_{00(2:1:1)} \left( z, l_{x,y}(2) \right) \right) 
\]  \( (13) \)
– Step 4, …, n+1
  • Any additional illuminant corresponding pixel
    – Only mapping into paramer mismatch gamut
      » Defining by previous transformations
      \[
P(\hat{I}_{x,y}(k-1), \ldots, \hat{I}_{x,y}(1))
      = L\left(X\left(I_k, \bigcap_{i=1}^{k-1} (I_i, \hat{I}_{x,y}(i)) \cap \mathcal{G}\right)\right)
\]
      (14)

Where \( \hat{I}_{x,y}(k-1), \ldots, \hat{I}_{x,y}(1) \) are the resulting CIELAB values for position \( x, y \) of previously performed transformations

– CIELAB values resulting from previous transformations
  » Changing without noticeably
    » Only reflectances considering lying within intersection of corresponding parameric

– Intersection is not empty
  » Construction of previous mappings
– Corresponding parameter mismatch gamut containing at least one CIELAB color

» Using for parameter mismatch-based gamut mapping

\[
\Gamma_{\text{Para}} \left[ I_k, \ldots, I_1, \mathcal{G}, \hat{L}_{k-1}, \ldots, \hat{L}_1 \right] : L_k \rightarrow \hat{L}_k
\]  

(15)

Where each pixel \( \hat{x}_{k, y}(k) \) of the image \( \hat{L}_k \) fulfills the condition

\[
\hat{x}_{k, y}(k) \in P \left( I_k, \ldots, I_1, \mathcal{G}, \hat{x}_{k, y}(k-1), \ldots, \hat{x}_{k, y}(1) \right)
\]  

(16)

– Obtaining \( n \) CIELAB images: \( \hat{L}_1, \ldots, \hat{L}_n \)

\[
\hat{L}_1 = \Gamma_{\text{Para}} \left[ I_1, \mathcal{G}(L_1) \right]
\]  

(17)

\[
\hat{L}_2 = \Gamma_{\text{Para}} \left[ I_2, I_1, \mathcal{G}, \hat{L}_1(L_2) \right]
\]  

(18)

\[
\vdots
\]

\[
\hat{L}_n = \Gamma_{\text{Para}} \left[ I_n, \ldots, I_1, \mathcal{G}, \hat{L}_{n-1}, \ldots, \hat{L}_1 \right](L_n)
\]  

(19)
– Step n+2:
  • Transforming set of gamut mapped CIELAB images back to reflectance space
    – Suitable reflectances defined by parameric set
      \[
      \hat{r}_{x,y}(\lambda) \in \bigcap_{i=1}^{n} \beta(I_i, \hat{I}_{x,y}(i)) \cap \mathcal{D}
      \] (20)
    – Gamut mapped CIELAB images reproducible by single print
      » Without noticeable differences
        » Each pixel position \((x,y)\)
      \[
      \Delta E\left[ L\left(X(I_i, \hat{r}_{x,y})\right), \hat{I}_{x,y}(i) \right] \leq \frac{D_{\text{JND}}}{2}, \quad i = 1, \ldots, n
      \] (21)
- Concept of parameter mismatch-based spectral gamut mapping

Fig. 1. Concept of the parameter mismatch-based spectral gamut mapping framework
◆ Properties of proposing method
  – Paramer comparing with metamer
    • Metamer considering intrinsic spectral variability
      – Adjusting reproduction to original for ordered illuminants
      – Only improving multiilluminant reproduction quality
        » By adding new inks to increasing spectral variability
    • Paramer considering observer-based color quantization
      – Color differences within fractions of JND
        » Reproductions perceiving similar
        » Without changing printing system
– Order of illuminants
  • Different order resulting in different spectrum
  • More colors to choosing
    – Under illuminants at beginning of ordered chain as under subsequent illuminant
  • Order choosing according to importance of illuminants in given application
    – Application providing none information
      » One objective for sorting
        » Deriving differences between original and reproduction
    – Original image containing paramers or metamers
      » Weighting importance of illuminants higher
    – Starting mapping without metamers or paramers
      » Lossing metameric or parameric colors
– Mixed illuminant conditions
  • Leaving CIELAB unchanging for considered illuminants
    – Reproductions matching with original
      » Any mixture of illuminants

– Gamut mapping of in-spectral-gamut images
  • Clipping transformations
    – Leaving in-gamut colors unchanging
      » Resulting transformation unchanging in-spectral-gamut reflectance
Investigating on a CMYKRGB printer

◆ Don’t conduct psychophysical experiments
  – Most important illuminant
    • Traditional gamut mapping method
  – Other illuminants
    • Color difference formulas
      – Basing on psychophysics

◆ spectral separation methodology
  – Investigating parameter framework
    • Calculating pixel dependent parameter mismatch gamuts
– Using Brute Force-Branch and Bound (BFBB)
  • Precise description of parameter gamuts
  • Approaching filters
    – Control value space of printer
  • Corresponding reflectances satisfying mapped CIELAB images
    – Reproducible by single print without noticeable differences
  • Too large considering number by BFBB
    – Most control values non-printable in practice
      » Exceeding maximum total ink coverage

– BFBB separation method
  • Using subset of control value space
    – Combination of four colorants
      » Including black ink
  • Difference between real gamut and resulting from control values
    – Assuming small
• Limiting number of overprints to four colorants
  – Size of spectral and colorimetric noise of resulting printout
  – Number of training colors fitting CYNSN
    » Requiring reasonable spectral accuracy
• Further reducing control combinations
  – Physical quantization
• BFBB approach

Fig. 2. Brute Force—Branch and Bound (BFBB) approach to test the parameter mismatch-based spectral gamut mapping method
CMYKRGB printing system

- Some inks spectrally redundant
  - Black and medium and light gray
- Considering seven inks
  - CMYKRGB
- Controlling by Onyx Graphics Production House
  - Allowing inks independent control
- Each of 20 four-colorant printers
  - Characterizing by CYNSN printer model
    - Utilizing five grid points in each colorant dimension
◆ Test images and illuminants

- Using two images for investigating
  - METACOW
    - Consisting of 24 cows spectrally rendered
      » Illuminant CIED65
        » Rear and front match
      » Illuminant CIEA
        » Large mismatch
Fig. 3. METACOW rendered for (a) CIED65 (b) CIEA
• Starry night

Fig. 4. Vincent van Gogh’s *The Starry Night*; acquired through the Lillie P. Bliss Bequest; permanent collection The Museum of Modern Art, New York.] (sRGB rendering).
Gamut mapping transformation

- Traditional gamut mapping transformation
  - Hue and lightness preserving clipping
    - Seven ink printer has large metameric gamut most images
      » Disturbing marginally under CIED65 and CIEA
  - Parameter mismatch-based mapping
    - Minimum transformation
Results and discussion

- METACOW with $I_1 = \text{CIED65}$ and $I_2 = \text{CIEA}$
  - CIED65 gamut of CMYKRGB printer is large
    - Reproducing with no colorimetric error
    - Exceptions
      - Dark colors of background
      - Highlights exceeding printer’s black point or paper white
Fig. 5. Beige (left column) and gray cow (right column). For the first illuminant (CIED65) both cows are within the metameric gamut of the printer and are reproducible without visible color shifts (top images). For the second illuminant (CIEA) the front part of the cows is not reproducible in a single print (middle images). The bottom figure shows the CIELAB (CIEA) location of a color at the cow’s...
– Illuminant CIEA
  • Rear part reproductions matching original
  • Exceptions
    – Rear part too small to covering gamut

Fig. 6. Right: shows the CIELAB (CIEA) location of a color at the yellow cow’s rear (circle) and at the cow’s front (star) that are metameric for illuminant CIED65. The filled area is the paramer mismatch gamut.
– Dealing two phenomena differing from traditional
  • Preserving hue cannot ensuring
    – Second or subsequent illuminants
    – Utilizing colorimetric gamut of printer with standard ink set
  • Chroma gain
    – Decreasing by traditional colorimetric gamut mapping
    – Exceptions
      » Presenting images on large gamut displays
– Original and reproduced spectra in Fig. 5.

**Fig. 7.** Original and reproduced spectra of the beige (left) and gray (right) cow’s rear and front. Reproductions are calculated using $I_1 = CIE D65$, $I_2 = CIE A$. 
METACOW with $I_1 = CIE_A$, $I_2 = CIE_D$

- Comparing to $I_1 = CIE_D$, $I_2 = CIE_A$
- Order of illuminants using for parameter mapping
  - Crucial for resulting reproduction
- using exclusively clipping transformations
  - Leaving in-gamut colors unchanged
    - Rear parts of cows invariant
Fig. 8. Beige (left column) and gray cow (right column). For the first illuminant (CIE A) both cows are within the metameric gamut of the printer and are reproducible without visible color shifts (top images). For the second illuminant (CIE D65) the front parts of the cows are not reproducible in a single print (bottom images).
◆ The Starry night
  – Investigating properties of parameter mapping
    • Applying on natural reflectances
    • Larger errors mainly resulting from dark colors
      – Exceeding chroma or lightness of printer’s black point
Fig. 9. Color difference maps (pixel-wise CIEDE2000) between the original and the reproduction. Top images: color difference map for tungsten gallery light as first illuminant (left) and CIED65 as second illuminant (right). Bottom images: color difference map for CIED65 as first illuminant (left).
**Table 1.** 95th percentiles of CIEDE2000 errors for different viewing illuminant

<table>
<thead>
<tr>
<th></th>
<th>$I_1 = D65$</th>
<th>$I_1 = Tungsten$</th>
<th>$I_2 = Tungsten$</th>
<th>$I_2 = D65$</th>
</tr>
</thead>
<tbody>
<tr>
<td>D65</td>
<td>2.3</td>
<td>4.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tungsten</td>
<td>4.7</td>
<td>2.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
- Cutout of original and reproduction
  - Under second illuminant CIED65

\[ I_2 \]

**Fig. 10.** Cutout comparison of original and reproduction under CIED65 that serves as the second illuminant for the gamut mapping.
Fig. 11. Two real prints captured by a Canon EOS 5D Mark II camera under illuminant CIED65 (top row) and CIEA (bottom row). The banding artifacts of the left print result from a nonsmooth separation. The artifacts can be avoided by adding some noise to the $a^*$ and $b^*$ channel of the CIELAB images before separation. Please note that the capturing process might induce some color errors.
Conclusion

◆ Spectral copy of original scene
  – Requiring visual match
    • Invariant viewing illuminant changes
  – Presenting spectral gamut mapping
    • Hierarchical set of illuminants
      – Subsequent transformations within 3D color spaces
        » Relating to human color vision