Illuminant and device invariant color using histogram equalization

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Graham Finlayson, Steven Hordley, Gerald Schaefer, and Gui Yun Tian

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

- Necessity of the *color invariant image representation*
  - Color can provide useful information for computer vision such as image retrieval, object recognition
  - Color must be independent of imaging condition such as scene illumination and imaging device

- A new color invariant image representation *based on the histogram equalization*
  - Presenting the empirical evidence that *rank ordering of sensor responses are preserved across a change in imaging condition*
    -> histogram equalization of each channel of a color image is invariant
  - Applying the method to an image indexing application
1. Introduction

- Color images (RGB)
  - Providing useful information to help in solving a wide range of computer vision
    - Image retrieval, image segmentation, object tracking
  - Assuming that color recorded by devices are an inherent property of the imaged objects

- Two kinds of dependence of color images
  - Illumination dependent
  - Device dependent
Method to account for illumination dependence

- Color invariant
  - Seeking transformations of the image data such that the transformed data are illuminant independent
  - More practical success than color constancy

- Color constancy
  - Determining an estimate of the light illuminating a scene and providing this estimate to subsequent vision algorithm
  - A more powerful solution to illumination dependence than color invariant
Addressing the limitations of existing color constancy and color invariant

- A new representation which is both illumination independent and device independent
  - Observing that the rank orderings of responses of a given are largely preserved
  - Revealing that the preservation of rank ordering holds both across a wide range of illuminants and a variety of imaging devices
  - Proposing the invariant representation using histogram equalization
Organization of this paper

- Showing how recorded responses depend on illuminant and device
- Describing a number of existing color invariants
- Presenting an empirical proof that rank orderings of sensor responses are invariant across a wide range of illuminants and device
- Proposing the invariant representation using the histogram equalization and demonstrating the utility of the technique
2. Background

Simple model of image formation

- Device response depends both on properties of sensor \( Q_k(\lambda) \) and prevailing illumination \( E_k(\lambda) \)

$$q_k = \int_{\omega} E(\lambda)S(\lambda)Q_k(\lambda)d\lambda, \quad k = 1,\ldots,m$$  \hspace{1cm} (1)

\( E(\lambda) \): spectral power distribution  
\( S(\lambda) \): surface reflectance  
\( Q_k(\lambda) \): spectral sensitivity function of the \( k \)th sensor
Image representation invariant to illuminant

- Chromaticity vector invariant to a change in intensity of an illuminant

\[ r = \frac{R}{R + G + B}, \quad g = \frac{G}{R + G + B}, \quad b = \frac{B}{R + G + B} \]  \hspace{1cm} (2)

- Simple illuminant invariant representation (diagonal model)

\[ R' = \frac{R}{R_{ave}}, \quad G' = \frac{G}{G_{ave}}, \quad B' = \frac{B}{B_{ave}} \]  \hspace{1cm} (3)

- Two common failings of existing invariant representation
  - Poor performance
  - Not consideration of the device invariance
Variation of response across device

- The properties of the three sensors of a device
  
  \[ q_k = \int_{\omega} E(\lambda) S(\lambda) Q_k(\lambda) d\lambda, \quad k = 1, \ldots, m \]  
  
- Nonlinear transformation known as the gamma of the monitor
  
  \[ q_k = \int_{\omega} E(\lambda) S(\lambda) Q_k(\lambda) d\lambda, \quad k = 1, \ldots, m \]  
  
- Tone curve correction to create a visually pleasing image
3. Rank invariance of sensor responses

- Rank invariance under a change of illumination
  - Under assumption of a diagonal model of illumination change
    \[ R_i^c = \alpha R_i^o \]
    \[ R_i^o : \text{response of a single sensor to a surface 'i' under an illuminant 'o'} \]
    \[ R_i^c : \text{response of a single sensor to a surface 'i' under an illuminant 'c'} \]
    \[ R_i^o > R_j^o \Rightarrow \alpha R_i^o > \alpha R_j^o \Rightarrow R_i^c < R_j^c \]

- Rank invariance to nonlinear function
  - Nonlinear function is monotonic
    \[ R_i > R_j \Rightarrow (R_i)^\gamma > (R_j)^\gamma \]
3-1. Rank invariance in practice

Further investigation of the rank invariance across changes in both illumination and device

- **Case 1**: a single device under changing illumination
  - `Rank()`: taking the vector argument and returning a vector whose elements contain the rank of the corresponding element in the argument

\[
rank(P_k^1) = rank(P_k^2)
\]

\[
P_k^1 = \int E^1(\lambda) R_k(\lambda) S(\lambda), \quad P_k^2 = \int E^2(\lambda) R_k(\lambda) S(\lambda)
\]

Different illuminant
Case 2: Invariance of rank ordering across devices

\[ \text{rank}(P_k^1) = \text{rank}(Q_k^1) \]

\[ P_k^1 = \int E^1(\lambda)R_k^1(\lambda)S(\lambda), \quad Q_k^1 = \int E^1(\lambda)R_k^2(\lambda)S(\lambda) \]

Different devices

Assessment of the rank using Spearman’s rank correlation coefficient

\[ \rho = 1 - 6\sum_{j=1}^{N} \frac{d_j^2}{N_s (N_s^2 - 1)}, \quad -1 < \rho < 1 \]

where \( N_s \): number of surfaces
\( d_j = \) difference between the \( j \)-th elements of \( \text{rank}(P_k^1) \) and \( \text{rank}(P_k^2) \)
Experiment and analysis for a variety of image devices and illuminants

- A set of 462 Munsell chips to represent a wide range of reflectances
- 16 different lights
  - Daylight, fluorescent, Planckian blackbody radiators
- Four digital camera, a flatbed scanner, color matching function

Fig. 1. Example of sensitivity functions for the long-wavelength
Results

Fig. 2. Correlation plot of long-wave Sensor responses to a set of surfaces Viewed under two different lights

Table 1. Spearman’s rank correlation coefficient

<table>
<thead>
<tr>
<th>Change in illuminant</th>
<th>Long-wave sensor</th>
<th>Medium-wave sensor</th>
<th>Short-wave sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Across illumination</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Colour matching</td>
<td>0.9957</td>
<td>0.9922</td>
<td>0.9992</td>
</tr>
<tr>
<td>functions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Camera 1</td>
<td>0.9983</td>
<td>0.9984</td>
<td>0.9974</td>
</tr>
<tr>
<td>Camera 2</td>
<td>0.9978</td>
<td>0.9938</td>
<td>0.9933</td>
</tr>
<tr>
<td>Camera 3</td>
<td>0.9979</td>
<td>0.9984</td>
<td>0.9972</td>
</tr>
<tr>
<td>Camera 4</td>
<td>0.9981</td>
<td>0.9991</td>
<td>0.9994</td>
</tr>
<tr>
<td>Scanner</td>
<td>0.9975</td>
<td>0.9989</td>
<td>0.9995</td>
</tr>
<tr>
<td>Across devices</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Daylight (D65)</td>
<td>0.9877</td>
<td>0.9934</td>
<td>0.9831</td>
</tr>
<tr>
<td>Fluorescent (cwf)</td>
<td>0.9931</td>
<td>0.9900</td>
<td>0.9710</td>
</tr>
<tr>
<td>Tungsten (A)</td>
<td>0.9936</td>
<td>0.9814</td>
<td>0.9640</td>
</tr>
<tr>
<td>Across device and illuminant</td>
<td>0.9901</td>
<td>0.9886</td>
<td>0.9774</td>
</tr>
</tbody>
</table>

Rows 1–6 show results for each sensor (R, G, and B) of a range of devices. Results are averaged over all pairs of a set of 16 illuminants. Rows 7–9 show results averaged over all devices for three different illuminants. Row 10 shows results averaged over six devices and 16 illuminants.
3-2. Rank invariance of image

- Equivalence class of images with respect to $I$
  - $I^1$ is equivalent to $I^2$ if the following is true: $\text{rank}(P_k^1) = \text{rank}(P_k^2)$
    - In other words, rank ordering of $I^1$ is same as $I^2$

$$\mathcal{I} = \{I^j | \text{rank}(P_k^j) = \text{rank}(P_k), \ k = 1, 2, 3\}. \quad (12)$$

- Rank invariance of image is achieved by determining whether or not two images belong to the same equivalence class
4. Histogram equalization for color invariance

- Cumulative invariance
  - Assuming that the illumination change preserves rank ordering of pixels
    \[
    P(R^c < R_i^c) = P(R^o < R_i^o) \quad : \quad R^o \in [0...R_{max}]
    \]
    \[
    P(R^c < R_i^c): \text{number of pixels in an image with a value less than or equal to } R_i^o
    \]

- A new image representation using histogram equalization
  - Transforming the image that the resulting image histogram is uniform

\[
R_i^{inv} = \frac{R_{max}}{N_{pix}} P(R^o \leq R_i^o) \quad \quad G_i^{inv} = \frac{G_{max}}{N_{pix}} P(G^o \leq G_i^o) \quad \quad B_i^{inv} = \frac{B_{max}}{N_{pix}} P(R^o \leq R_i^o)
\]

where \(N_{pix}: \text{number of pixels}\)
The effect of applying the histogram equalization

- First row shows three images of the same scene, captured by the same camera under three different illuminant.
- Second row shows the resulted images.
The effect of applying the histogram equalization

- First two column: captured images with different devices
- Second two column: histogram equalized images
5. An application to color indexing

- Applying this method to an image retrieval task
  - Database image
    - 28 different color textures captured under six different device (four camera and two scanner) and three different lights
  - Three different conditions
    - Change in illumination
    - Change in device
    - Change of both device and illumination
Experimental procedure

- Choosing a set of 28 images all captured under the same condition to be image database
- Selecting from the remaining set of images a subset of appropriate query images
- Deriving the invariant image for all database and query image
- Representing the invariant image by color distribution (histogram)
- Performing the indexing by comparing its histogram
Block of the experimental procedure

Image invariant

Histogram intersection method

\[ \sum_{i,j} \min[H_1(i, j), H_2(i, j)] \]

\[ \sum_{i,j} H_1(i, j) \]

where \( H_1 \) and \( H_2 \) : histogram

Database
### Indexing performance

#### Matching percentile (MP)

The matching percentile (MP) is defined as:

$$\gamma = \frac{N_{\text{model}} - \text{rank}}{N_{\text{model}} - 1}, \quad 0 \leq \gamma \leq 1$$

- $\gamma = 1 \rightarrow$ image was correctly matched
- $\gamma = 0 \rightarrow$ correct image was in last place

where $N_{\text{model}}$ is the number of database images, and rank is the position of the correct histogram in a sorted list of histogram intersection scores.

#### AMP

Multiply the MP by 100 and averaging over all matched images.
Results

Table 2. Result of indexing experiment over a change in illuminant

<table>
<thead>
<tr>
<th>Colour model</th>
<th>Camera 1</th>
<th>Camera 2</th>
<th>Camera 3</th>
<th>Camera 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Greyworld</td>
<td>96.23</td>
<td>81.59</td>
<td>99.12</td>
<td>98.90</td>
</tr>
<tr>
<td>Hist. eq.</td>
<td>99.25</td>
<td>92.35</td>
<td>96.91</td>
<td>98.37</td>
</tr>
</tbody>
</table>

Table 3. Result of indexing experiment over a change of camera

<table>
<thead>
<tr>
<th>Colour model</th>
<th>Camera 1</th>
<th>Camera 2</th>
<th>Camera 3</th>
<th>Camera 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Greyworld</td>
<td>95.81</td>
<td>89.92</td>
<td>93.67</td>
<td>97.50</td>
</tr>
<tr>
<td>Hist. eq.</td>
<td>98.16</td>
<td>92.34</td>
<td>93.62</td>
<td>98.99</td>
</tr>
</tbody>
</table>

Table 4. Result of indexing experiment over a change of device and illuminant

<table>
<thead>
<tr>
<th>Colour model</th>
<th>Cameras</th>
<th>Scanners</th>
<th>All devices</th>
</tr>
</thead>
<tbody>
<tr>
<td>Greyworld</td>
<td>92.77</td>
<td>89.36</td>
<td>92.28</td>
</tr>
<tr>
<td>Hist. eq.</td>
<td>94.99</td>
<td>88.48</td>
<td>94.54</td>
</tr>
</tbody>
</table>
6. Discussion

- Outperforming all previous invariant methods
- Giving the excellent performance across changes in illumination
- Investigation for poor performance
  - A number of images captured under tungsten illumination have values of zero in blue channel
  - Scanning process introduces significant non-uniformities