Multipsectral High Dynamic Range Imaging

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Abstract

- Capturing natural scene with high dynamic range content
  - Conventional method
    • Using conventional RGB cameras
      - Appearance of saturated and underexposed areas
      - Appearing lacks of color accuracy
  - Proposed method
    • Application of high dynamic imaging
      - Increase of dynamic range
        » Combining several RGB images of different exposures into one image
      - Improvement of color accuracy
        » Using multispectral camera
Introduction

- Drawback of the most common camera type
  - Appearance of systematic color error
    - Because of violating Luther rule
  - Disadvantage from camera filter array
    - Requiring spatial interpolation of color information
    - Appearance of shift variance
Multispectral camera
  - Providing greatly improved color accuracy
    • Application of wheel with optical bandpass filters between lens and gray level imaging sensor

Fig. 1. Our multispectral camera (left) and a sketch of its internal configuration (right).
- Approach of multispectral HDR imaging
  - Method using two RGB cameras
    - Composition
      - Use of half mirror
        » Division of light
      - Use of neutral density filter
        » Controlling amount of light
      - Use of different interference filters
        » Filtering specific spectrum
    - Disadvantage
      - Using limited number of two exposure levels
      - Appearing saturation in one half of passband
  - Proposed method
    - No limitation about certain number of exposure levels
    - Acquisition of full spectral range for each exposure level
      - Providing greater dynamic range
Acquisition model for HDR imaging

- Mathematical model of the imaging chain

**Fig. 2.** Diagram of physical model using continuous variables.
– Optical bandpass filters and camera transfer function

Fig. 3. Spectral and radiometric characteristic curves of our multispectral camera. (a) Joint spectral characteristics $H_i(\lambda)$ of optical bandpass filters $T_i(\lambda)$ and sensor $R(\lambda)$. (b) Camera transfer function $f$ of our internal gray level camera Sony XCD-SX900.
- Spectral irradiance reaching sensor surface

\[ E_i(\lambda) = S(\lambda) \beta(\lambda) o(\lambda) \tau_i(\lambda) \quad (1) \]

- Spectral radiant power

\[ \phi(\lambda) = E_i(\lambda) R(\lambda) A \quad (2) \]

- Integrating over whole wavelength range

\[ \phi_i = \int_\lambda \phi(\lambda)d\lambda = \int_\lambda S(\lambda) \beta(\lambda) o(\lambda) a\tau_i(\lambda) R(\lambda) Ad\lambda \quad (3) \]

- Spectral radiant energy

\[ Q_{i,j} = \phi_i T_{i,j} \quad (4) \]
– Final camera value
  • Application of CTF
    – Opto-electronic conversion of radiant energy to camera value

\[ q_{i,j} = f(Q_{i,j}) \]  \hspace{1cm} (5)

• Combination of Eq. (1) to (5)

\[ q_{i,j} = f(T_{i,j} \int S(\lambda) \beta(\lambda) o(\lambda) a\tau_i(\lambda) R(\lambda) Ad\lambda) \]  \hspace{1cm} (6)

• Simplification of Eq. (6)

\[ q_{i,j} = f(T_{i,j} \int kH_i(\lambda) S(\lambda) \beta(\lambda) d\lambda) \]  \hspace{1cm} (7)
Discrete representation of imaging chain

- Sampling wavelength range from $\lambda_1=400\text{nm}$ to $\lambda_N=700\text{nm}$
  
  • Expression of Eq. (4) and (5) by matrix notation

  $$q_{i,j} = f(T_j \phi)$$  \hspace{1cm} (8)

  - Inserting Eq. (9) to (8)

  $$\phi = kHS\beta$$  \hspace{1cm} (9)

  • Expression of complete model from Eq. (7)

  $$q_j = f(T_jkHS\beta)$$  \hspace{1cm} (10)
- Expression of integration in Eq.(7)

\[ q_{i,j} = f \left( T_{i,j} \sum_{n=1}^{N} k H_i (\lambda_n) S (\lambda_n) \beta (\lambda_n) \right) \]  

(11)

- Expression of each factor by matrix notation

\[
q_j = \left( q_{1,j} \cdots q_{l,j} \right)^T 
\]

\[
\phi = \left( \phi_1 \cdots \phi_l \right)^T 
\]

\[
T_j = \text{diag} \left( T_{1,j} \cdots T_{l,j} \right) 
\]

\[
H_i = \left( H_i (\lambda_1) \cdots H_i (\lambda_N) \right)^T 
\]

\[
H = \left( H_1 \cdots H_l \right)^T 
\]

\[
S = \text{diag} \left( S (\lambda_1) \cdots S (\lambda_N) \right) 
\]

\[
\beta = \left( \beta (\lambda_1) \cdots \beta (\lambda_N) \right)^T 
\]
Estimation

- Estimating HDRI part
  - Inversion of Eq. (8)
    \[
    \hat{\phi}_i = \frac{\sum_{j=1}^{J} f^{-1}(q_{i,j}) \omega(q_{i,j})}{\sum_{j=1}^{J} \omega(q_{i,j})} = \frac{\sum_{j=1}^{J} O_{i,j} \omega(q_{i,j})}{\sum_{j=1}^{J} \omega(q_{i,j})}
    \]

- Application of weighting function
  - Suppression of saturated values
    \[
    \omega(d) = \begin{cases} 
    1.0 & 0 \leq |d| \leq \alpha \frac{D}{2} \\
    \frac{1}{2} \left[ 1 + \cos \left( \pi \frac{d - \alpha \frac{D}{2}}{2(1-\alpha)\frac{D}{2}} \right) \right] & \alpha \frac{D}{2} \leq |d| \leq \frac{D}{2} 
    \end{cases}
    \]
Fig. 4. Windowing function $\omega(\cdot)$: Turkey window with length $D+1=256$ and taper ratio $\alpha=0.5$. 
– Spectral estimation

- Inversion of Eq. (9)
  - Application of Eq. (9)
    \[ \phi = kS'H\beta \] (14)

  » Use of white balance reference card with known spectrum \( \beta_{\text{ref}} \) and camera response \( \Phi_{\text{ref}} \)
    \[ S'_{\text{ref}} = \text{diag}\left( \phi_{\text{ref}} \div (kH\beta_{\text{ref}}) \right) \] (15)

- Inserting Eq. (15) to (14)
  \[ \phi = k\text{diag}\left( \phi_{\text{ref}} \div (kH\beta_{\text{ref}}) \right)H\beta \] (16)

- Simplification of Eq. (16)
  \[ \left( \phi \div \phi_{\text{ref}} \right) \circ \left( H\beta_{\text{ref}} \right) = H\beta \] (17)
- Approximation of reflectance

\[
\hat{\beta} = H_{\text{inv}} \left( (\phi \div \phi_{\text{ref}}) \circ (H \beta_{\text{ref}}) \right) \quad (18)
\]

» Using weighted pseudoinverse

\[
H_{\text{inv}} = R_{xx}^{-1} H^T \left( H R_{xx}^{-1} H^T \right) \quad (19)
\]

\[
R_{xx}^{-1} = \begin{pmatrix}
1 & \rho & \rho^2 & \ldots & \rho^{N-1} \\
\rho & 1 & \rho & \ldots & \rho^{N-2} \\
\rho^2 & \rho & 1 & \ldots & \\
& \ldots & \ldots & \rho & \\
\rho^{N-1} & \rho^{N-2} & \ldots & \rho & 1
\end{pmatrix} \quad (20)
\]
Practical considerations

☐ Measuring CTF
  - Requiring linearization of camera values
    • Occurrence of severe errors on final measurement
      • Application of inverse CTF
        \[ Q_{i,j} = f^{-1}(q_{i,j}) \] (21)
  - Measurement of CTF by equipment
    • Use of relative radiometric measurement with calibration stand
      \[ E \sim \frac{r^2}{r^2 + x^2} L \] (22)

where \( E \) is the irradiance, \( L \) is the radiance, \( r \) is the opening diameter of sphere, and \( x \) is the distance between light source and camera sensor.
Fig. 5. Our camera transfer function (CTF) measurement stand
 Acquisition procedure
  – Acquisition of images with different exposures and channels
    • Use of Macbeth ColorChecker with 24 color patches

Fig. 6. All images taken for an acquisition with seven spectral channels $I=7$ (left to right) and three exposure levels $J=3$ (top to bottom).
Visualizing each histogram of single image from exposure time series

Fig. 7. Histograms of normalized images with different exposure times.
Multispectral data exchange
- Use of .aix file format for multispectral HDR images
  - Producing floating point data
    - Including details in dark and bright regions
      » Storing values from Eq. (18)

\[ \left( \phi \div \phi_{\text{ref}} \right) \circ (H\beta_{\text{ref}}) \quad (23) \]

Experiments
- Acquisition of images with 7 exposure times for 7 spectral channels
  - Use of Macbeth ColorChecker SG with 140 color patches
  - Use of halogen lamp
Results

- Visualizing analysis of SNR improvement between LDR and HDR acquisition

**Fig. 8.** Comparison of the signal to noise ratio of LDR/HDR acquisitions of a ColorChecker with 140 color patches.
Visualizing measurements of color accuracy

- Use of Macbeth EyeOne spectral photometer

Fig. 9. Comparison of spectral error $\Delta E_{00}$.
Acquisition of outdoor scenes

Fig. 10. HDR image of Aachen's city hall.
**Fig. 11.** Detail crops of Fig. 10 showing the improvements of HDR imaging; left images: LDR, right images: HDR.
Conclusion

- Multispectral high dynamic range imaging method
  - Combination of two methods
    - HDR imaging
    - Multispectral imaging
  - Advantage
    - Improvement of color accuracy
    - Improvement of signal to noise ratio
    - Improvement of applicability for outdoor images