Adaptive Height – Modified Histogram Equalization and Chroma Correction in YCbCr Color Space for Fast Backlight Image Compensation

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Abstract

◆ Adaptive height – modified histogram equalization (AHMHE)
  – Compensation technique for backlight images
    • Enhancing contrast in both the dark and bright areas

◆ Chroma correction technique
  – Applying chroma components in the YCbCr color space
    • Producing more vivid color images
Introduction

◆ Backlight image
  – Backlight condition
    • Over-illuminating background relative to the main object in the focal region
  – Appearing backlit region in a backlight image
    • Saturating entire image

◆ Backlight image compensation
  – Enhancing contrast in the main object of the photograph
    • Adding luminance compensation to the dark region
Fig. 1. Example of backlight image and its luminance histogram.
Histogram equalization for contrast enhancement

Classification of methods using the histogram
  - Dividing two types by the influence range of their mapping function
    - Global histogram equalization (GHE)
      - Including HE and bin underflow bin overflow HE (BUBO HE)
        » Simple and fast
        » Appearing regions of decreased local contrast
    - Local histogram equalization (LHE)
      - Including adaptive HE (AHE), and contrast limited adaptive HE (CLAHE)
        » Appearing images with good local contrasts
        » Requiring high computational loads
Histogram equalization (HE)

- Feature
  - Using histogram information of the image
  - Turning information into image with uniform histogram distributions

- Shortcoming
  - Use of global information from the whole image
  - Not considering local information of luminance variation within neighborhoods of each pixel
Fig. 2. HE resultant image and its luminance histogram.
◆ Bin underflow bin overflow HE (BUBO HE)

– Feature
  • Prevention of sharp up-swings in the mapping function
    – Limitation of the compensation level
    – Compensation of the regions of having low intensity
      » Adjusting slope in the mapping function

– Shortcoming
  • Controlling some parts of the mapping function by threshold
    – Becoming straight line
  • Not addressing decreased local contrast problem
Fig. 3. BUBO HE resultant image and its luminance histogram.
◆ Adaptive HE (AHE)
  – Overcoming decrease in the local contrast
    • Generating mapping function for each pixel from the histogram in the surrounding window
  – Shortcoming
    • Requiring significant increase in computation
◆ Contrast Limited Adaptive HE (CLAHE)
  – Generalization of the adaptive HE (AHE)
  • Feature
    – Reduction of the computational burden
      » Use of a block unit process
  • Shortcoming
    – Not use of the whole dynamic range of the histogram
      » Causing decrease in the contrast
      » Leaving foggy images
    – Increasing computational requirements
      » Minimization of the small block
Fig. 4. CLAHE resultant image and its luminance histogram.
Adaptive height - modified histogram equalization (AHMHE)

- Improvement of a visual qualities in backlight images
  - Producing high contrast in all parts of resultant images
    - Enhancing the contrast in both dark and bright areas
      » Minimizing regions with decreased local contrast
  - Maintaining very low computational complexity
– Procedure

  • Development of the mapping function
    – Using adaptively height-modified histograms through power operation
  • Enhancement of the local contrast
    – Use of considering the relationships between adjacent pixels
    – Defining the local contrast map
      » Using difference operations of luminance (Y) components with blurred Y
  • Application of the chroma correction
    – Getting vivid color images
      » Considering luminance change
Fig. 5. The structure of adaptive height - modified histogram equalization.
Adaptive height - modified histogram equalization

◆ Use YCbCr color space

- Preserving detailed information of luminance component
  • Exploiting this property in chroma correction
- Transformation process
  • RGB color space to YCbCr color space

\[
\begin{bmatrix}
Y \\
Cb \\
Cr
\end{bmatrix} = \begin{bmatrix}
16 \\
128 \\
128
\end{bmatrix} + \begin{bmatrix}
65.481 & 128.553 & 24.966 \\
-37.797 & -74.203 & 112.000 \\
112.000 & -93.786 & -18.241
\end{bmatrix}
\]

where \(Y : [16, 235], Cr : [16, 240]\) and \(Cb : [16, 240]\).
\(R : [0, 1], G : [0, 1]\) and \(B : [0, 1]\).
◆ Design the mapping function
  – Mapping function of the standard HE
    • Expression
      – Taking probability distribution of the image probability density $P(k)$
        $$P(k) = \frac{h(k)}{N} \text{ for } k = 0,1,...,L-1 \text{ (Gray-level)}$$ (1)
        where $h(k)$ = # of pixels with gray-level $k$, $N$ = total # of pixels.
      – Obtaining image probability distribution or cumulative density function (c.d.f)
        $$C(k) = \sum_{m=0}^{k} P(m) \text{ for } k = 0,1,...,L-1 \text{ (Gray-level)}$$ (2)
Determining mapping function from the cumulative density function

\[ \tilde{k} = (L - 1) \times C(k) \]  

where \( k \) represent the input luminance gray-level and \( \tilde{k} \) denotes the transformed output luminance gray-level.

**Result**

**Fig. 6.** Mapping function of standard HE.
- Mapping function of the BUBO HE
  - Preventing any sudden increase of the mapping function
    - Generating histogram
      » Use to thresholds

$$h_{BUBO}(k) = \begin{cases} 
  \text{Over Threshold}, & h(k) \geq \text{Over Threshold} \\
  \text{Under Threshold}, & h(k) \geq \text{Under Threshold} \\
  h(k), & \text{otherwise}
\end{cases}$$

Fig. 7. (a). Original luminance histogram.
• Result

Fig. 7. (b). BEBO HE luminance histogram.

Fig. 7. (c). BEBO HR mapping function.
– Mapping function of AHMHE

• Expression
  – Modification of the histogram
    \[ h_i(k) = \alpha(h(k))^\frac{1}{n} \]  \hspace{1cm} (5)
    where constant \( \alpha \) used must be chosen such that the sum of the
    p.d.f is 1.
  – Obtaining final p.d.f
    \[ P_{AHMHE}(k) = \frac{h_i(k)}{N} = \frac{(h(k))^{1/n}}{\sum_{m=0}^{L-1} (h(m))^{1/n}} \]  \hspace{1cm} (6)
    where \( m \) is luminance gray-level ranging from 0 to \( L - 1 \).
– Obtaining c.d.f
\[ C_{AHMHE}(k) = \sum_{i=0}^{k} P_{AHMHE}(i) = \sum_{i=0}^{k} \frac{(h(i))^{1/n}}{\sum_{m=0}^{L-1}(h(m))^{1/n}} \]  \hspace{1cm} (7)

– Generating final mapping function
\[ \tilde{k}_{AHMHE} = (L - 1) \times C_{AHMHE}(k) = (L - 1) \times \frac{\sum_{i=0}^{k} (h(i))^{1/n}}{\sum_{m=0}^{L-1}(h(m))^{1/n}} \]  \hspace{1cm} (8)

– Changing height in the histogram
\[ h_{AHMHE}(k) = (h(k) + 1)^{1/n} \]  \hspace{1cm} (9)

where \( k \) represent the input luminance gray-level, \( h \) denotes the histogram and \( n \) is power constant that is set to be bigger than 1.0 to attenuate the height in the histogram.
• Result
  – Reducing height difference of the histogram
  – Not preventing sudden increase of the mapping function
  – Not compensating contrast in some areas
    » Having small distribution
  – Retaining profile shape of the histogram

Fig. 8. Method of construction the mapping function in AHMHE. (a) Normalized original luminance histogram. (b) Normalized AHMHE luminance histogram. (c) AHMHE mapping function.
• Role of the power operation parameter $n$
  – Affecting contrast of the resultant images

**Fig. 9.** The effect of power constant in AHMHE mapping function.
According to the input condition

\[
    n = \max(1, 1 + \text{Ratio of Low luminance area} - \text{Ratio of High luminance area})
\]  \hspace{1cm} (10)

**Table 1.** VCM (visual contrast measure) score test of resultant images with different parameter.
◆ Adding the local contrast map
  – Persisting some regions of decreased local contrast
    • Application of a contrast map
      – Having luminance difference information in the pixel neighborhood

Fig. 10. Local contrast map.
Generating two sub LCM (local contrast map)

\[
\text{Sub } LCM_1(i, j) = Y(i, j) - \frac{1}{9} \sum_{m,n=-1}^{1} Y(i-m, j-n)
\]

\[
\text{Sub } LCM_2(i, j) = Y'(i, j) - \frac{1}{9} \sum_{m,n=-1}^{1} Y'(i-m, j-n)
\]

where \( Y \) is the luminance component of the YCbCr color space.

\( Y' \) is the luminance component after applying the mapping function.

![Fig. 11. Sub local contrast map. (a) sub LCM 1 (b) sub LCM 2.](image-url)
» Generating local contrast map by a weighted sum approach

\[
LCM(i, j) = (Y(i, j) / 255) \times sub\ LCM_1(i, j) + (1 - (Y(i, j) / 255)) \times sub\ LCM_2(i, j)
\]  
(12)
◆ Chroma correction
  – Making resultant images with high color purity
    • Methods of using color spaces
      – Getting resultant images with low color purity
        » Formula of the transformation

\[
R_{out} = \frac{Y_{Enhanced}}{Y_{in}} \times R_{in}, \quad G_{out} = \frac{Y_{Enhanced}}{Y_{in}} \times G_{in}, \quad B_{out} = \frac{Y_{Enhanced}}{Y_{in}} \times B_{in}
\]  

(13)

where \(Y_{in}\) is the original luminance value of the pixel and \(Y_{Enhanced}\) is the enhanced luminance value.

» Based on changing only the luminance or intensity component
Other components

\[
Y_{out} = Y_{Enhanced}, \quad Cb_{out} = Cb_{in}, \quad Cr_{out} = Cr_{in}
\]

\[
Y_{out} = Y_{Enhanced}, \quad I_{out} = I_{in}, \quad Q_{out} = Q_{in}
\]

\[
H_{out} = H_{in}, \quad S_{out} = S_{in}, \quad I_{out} = I_{Enhanced}
\]

\[
H_{out} = H_{in}, \quad S_{out} = S_{in}, \quad V_{out} = V_{Enhanced}
\]

(14)

Proposed chroma correction method

– Use of YCbCr color space

• Preserving luminance detail information

\[
Y_{out} = Y_{AHMHE}
\]

\[
Cb_{out} = s \times \left( Y_{AHMHE} / Y_{in} \right) \times (Cb_{in} - 128) + 128
\]

\[
Cr_{out} = s \times \left( Y_{AHMHE} / Y_{in} \right) \times (Cr_{in} - 128) + 128
\]

(15)
Fig. 12. The comparison of color resultant image with different color space. (a) Original luminance Y (b) AHMHE result luminance. (c) RGB color space result (d) HSV color space result (f) Proposed chroma correction.
Experiments

◆ Evaluation of the algorithm performance
  – Using variety of backlight images

Fig. 13. The comparison of each algorithm. Images from left to right represent: the original backlight images, the CLAHE produced images, the BUBO HE Enhanced images, and the AHMHE resultant images respectively.
Fig. 13. The comparison of each algorithm. Images from left to right represent: the original backlight images, the CLAHE produced images, the BUBO HE Enhanced images, and the AHMHE resultant images respectively.
◆ Subjective evaluations
  – Score range
    • From 0 (bad) to 10 (best)

Table 2. Average of rated scores by 22 panels.

<table>
<thead>
<tr>
<th>Fig. 13</th>
<th>(a)</th>
<th>(b)</th>
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<th>(g)</th>
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<th>(j)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original Image</td>
<td>1.45</td>
<td>1.36</td>
<td>1.95</td>
<td>3.41</td>
<td>1.77</td>
<td>1.59</td>
<td>1.18</td>
<td>1.36</td>
<td>1.41</td>
<td>1.09</td>
</tr>
<tr>
<td>CLAHE</td>
<td>4.27</td>
<td>4.32</td>
<td>4.82</td>
<td>5.86</td>
<td>5.05</td>
<td>4.36</td>
<td>6.00</td>
<td>6.59</td>
<td>6.05</td>
<td>6.91</td>
</tr>
<tr>
<td>BUBO HE</td>
<td>6.23</td>
<td>5.86</td>
<td>6.27</td>
<td>5.86</td>
<td>6.73</td>
<td>7.50</td>
<td>5.32</td>
<td>5.23</td>
<td>6.55</td>
<td>5.77</td>
</tr>
<tr>
<td>AHMHE</td>
<td>8.32</td>
<td>7.95</td>
<td>8.64</td>
<td>7.64</td>
<td>7.32</td>
<td>8.73</td>
<td>7.18</td>
<td>5.86</td>
<td>7.05</td>
<td>6.73</td>
</tr>
</tbody>
</table>
Index evaluations related to contrast in brightness

– Comparing AHMHE with BUBO HE and CLAHE

• Application of the VCM (visual contrast measure)

\[ VCM = 100 \times \frac{R_v}{R_t} \]  

where \( R_v \) is the number of regions in an arbitrary image that exceed a specific threshold for regional standard deviation, and \( R_t \) is the total number of regions into which the image has been divided.
- VCM score

**Table 3.** VCM scores (%).

<table>
<thead>
<tr>
<th>Fig. 13</th>
<th>(a)</th>
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<th>(g)</th>
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<th>(j)</th>
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<tbody>
<tr>
<td>Original image</td>
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<td>37</td>
<td>31</td>
<td>44</td>
<td>36</td>
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<td>49</td>
<td>45</td>
<td>36</td>
<td>42</td>
</tr>
<tr>
<td>CLAHE</td>
<td>44</td>
<td>34</td>
<td>31</td>
<td>45</td>
<td>35</td>
<td>11</td>
<td>51</td>
<td>43</td>
<td>46</td>
<td>42</td>
</tr>
<tr>
<td>BUBO HE</td>
<td>61</td>
<td>37</td>
<td>54</td>
<td>53</td>
<td>54</td>
<td>35</td>
<td>49</td>
<td>54</td>
<td>49</td>
<td>42</td>
</tr>
<tr>
<td>AHMHE</td>
<td>69</td>
<td>60</td>
<td>63</td>
<td>64</td>
<td>61</td>
<td>69</td>
<td>67</td>
<td>64</td>
<td>55</td>
<td>48</td>
</tr>
</tbody>
</table>
• Application of CPP (Contrast per pixel)

\[
CPP = \frac{\sum_{i=1}^{r} \sum_{j=1}^{c} \left( \sum_{m,n=-1}^{1} |Y(i, j) - Y(i + m, j + n)| \right)}{r \times c}
\]

where \((i, j)\) is the individual pixel position, \(Y(i, j)\) is the luminance value of each pixel, and \(rc\) is the size of the image.

– CPP value
  » Meaning average of absolute difference of luminance value with the adjacent pixels

**Table 4.** CPP value.

<table>
<thead>
<tr>
<th>Fig. 13</th>
<th>(a)</th>
<th>(b)</th>
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<th>(g)</th>
<th>(h)</th>
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<th>(j)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original image</td>
<td>4.86</td>
<td>4.4</td>
<td>5.35</td>
<td>6.84</td>
<td>4.1</td>
<td>2.41</td>
<td>4.99</td>
<td>4.48</td>
<td>2.82</td>
<td>3.75</td>
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<td>CLAHE</td>
<td>5.99</td>
<td>4.43</td>
<td>6.38</td>
<td>7.22</td>
<td>3.6</td>
<td>2.8</td>
<td>5.11</td>
<td>4.55</td>
<td>3.21</td>
<td>3.93</td>
</tr>
<tr>
<td>BUBO HE</td>
<td>7.42</td>
<td>4.35</td>
<td>9.25</td>
<td>8.85</td>
<td>5.7</td>
<td>5.24</td>
<td>5.23</td>
<td>4.4</td>
<td>3.08</td>
<td>4.09</td>
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<tr>
<td>AHMHE</td>
<td>13.39</td>
<td>8.45</td>
<td>17.42</td>
<td>17.05</td>
<td>10.78</td>
<td>11.52</td>
<td>10.55</td>
<td>7.27</td>
<td>5.17</td>
<td>7.43</td>
</tr>
</tbody>
</table>
Index evaluations related to saturation

– Evaluation of the chroma correction performance

• Upgrading saturation to generate more vivid and colorful images

– Definition of the saturation in the RGB color space

$$Saturation = \sqrt{\frac{(R - \mu)^2 + (G - \mu)^2 + (B - \mu)^2}{3}}, \quad \mu = \frac{R + G + B}{3}$$

where $\mu$ is the mean of all the components.
Table 5. Saturation in RGB color space.

<table>
<thead>
<tr>
<th>Fig. 13</th>
<th>(a)</th>
<th>(b)</th>
<th>(c)</th>
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<th>(g)</th>
<th>(h)</th>
<th>(i)</th>
<th>(j)</th>
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<tbody>
<tr>
<td>Original image</td>
<td>7.21</td>
<td>6.42</td>
<td>2.66</td>
<td>7.50</td>
<td>3.89</td>
<td>6.56</td>
<td>3.48</td>
<td>4.80</td>
<td>4.09</td>
<td>4.74</td>
</tr>
<tr>
<td>YCbCr color space</td>
<td>7.08</td>
<td>6.33</td>
<td>2.48</td>
<td>6.85</td>
<td>3.61</td>
<td>6.43</td>
<td>3.42</td>
<td>4.53</td>
<td>3.84</td>
<td>4.52</td>
</tr>
<tr>
<td>processing</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RGB color space processing</td>
<td>12.85</td>
<td>10.74</td>
<td>5.55</td>
<td>9.19</td>
<td>6.75</td>
<td>18.67</td>
<td>6.54</td>
<td>6.64</td>
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<td>7.04</td>
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<td>15.64</td>
<td>10.93</td>
<td>9.00</td>
<td>9.31</td>
<td>8.41</td>
<td>24.92</td>
<td>17.48</td>
<td>7.25</td>
<td>7.01</td>
<td>9.86</td>
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<tr>
<td>Chroma correction</td>
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<td>8.84</td>
<td>11.38</td>
<td>8.59</td>
<td>23.21</td>
<td>13.48</td>
<td>8.35</td>
<td>7.53</td>
<td>9.52</td>
</tr>
</tbody>
</table>
Definition of the colorfulness

\[
\text{Colorfulness} = \sigma_{ab} + 0.94 \cdot \mu_c
\]  

(19)

where \( \sigma_a, \sigma_b \) is the variance of chroma components in CIELab color space, \( \sigma_{ab} \) calculated by \( \sqrt{\sigma_a + \sigma_b} \), \( \mu_c \) is the mean of \( C \) component and \( C(i, j) \) calculated by \( \sqrt{a(i, j)^2 + b(i, j)^2} \).

» Changing the CIELab color space from RGB color space

\[
C_{\text{linear}} = \begin{cases} 
C_{\text{RGB}} / 12.92 & C_{\text{RGB}} \leq 0.04045 \\
((C_{\text{RGB}} + 0.055) / 1.055)^{2.4} & C_{\text{RGB}} > 0.04045
\end{cases}
\]

where \( C = \{R, G, B\} \)

\[
\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.4125 & 0.3576 & 0.1804 \\ 0.2127 & 0.7152 & 0.0722 \\ 0.0193 & 0.1192 & 0.9502 \end{bmatrix} \begin{bmatrix} R_{\text{linear}} \\ G_{\text{linear}} \\ B_{\text{linear}} \end{bmatrix} \]

\[
\begin{bmatrix} X_n \\ Y_n \\ Z_n \end{bmatrix} = \begin{bmatrix} X / 0.950456 \\ Y / 1 \\ Z / 1.088754 \end{bmatrix}
\]

\[
L = 116 \times f(Y_n) - 16, \quad a = 500 \times \{f(X_n) - f(Y_n)\}, \quad b = 200 \times \{f(Y_n) - f(X_n)\}
\]

where \( f(t) = \begin{cases} 
 t^{1/3} & \text{at } t > 0.008856 \\
 7.787 \times t + 16 / 116 & \text{otherwise}
\end{cases} \)
**Table 6. Colorfulness.**

<table>
<thead>
<tr>
<th></th>
<th>(a)</th>
<th>(b)</th>
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<th>(d)</th>
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<th>(f)</th>
<th>(g)</th>
<th>(h)</th>
<th>(i)</th>
<th>(j)</th>
</tr>
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<tbody>
<tr>
<td>Original image</td>
<td>15.34</td>
<td>14.03</td>
<td>8.97</td>
<td>16.46</td>
<td>9.23</td>
<td>12.85</td>
<td>11.31</td>
<td>11.33</td>
<td>11.20</td>
<td>10.56</td>
</tr>
<tr>
<td>YCbCr color space processing</td>
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<td>11.61</td>
<td>6.33</td>
<td>14.21</td>
<td>7.53</td>
<td>8.54</td>
<td>7.88</td>
<td>9.59</td>
<td>8.84</td>
<td>8.73</td>
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<td>14.93</td>
<td>34.54</td>
<td>34.44</td>
<td>15.92</td>
<td>17.03</td>
<td>18.98</td>
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<td>24.89</td>
<td>22.49</td>
<td>23.77</td>
<td>15.68</td>
<td>31.78</td>
<td>41.99</td>
<td>17.90</td>
<td>17.33</td>
<td>18.24</td>
</tr>
</tbody>
</table>
**Processing time**

**Table 7.** Process time (second).

<table>
<thead>
<tr>
<th>Fig. 13</th>
<th>(a)</th>
<th>(b)</th>
<th>(c)</th>
<th>(d)</th>
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<th>(f)</th>
<th>(g)</th>
<th>(h)</th>
<th>(i)</th>
<th>(j)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Image size (Row × Column)</td>
<td>280×280</td>
<td>226×361</td>
<td>320×204</td>
<td>640×475</td>
<td>1023×769</td>
<td>512×768</td>
<td>640×352</td>
<td>600×400</td>
<td>600×400</td>
<td>640×480</td>
</tr>
<tr>
<td>CLAHE</td>
<td>0.58</td>
<td>0.58</td>
<td>0.50</td>
<td>2.13</td>
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Conclusion

◆ Proposed method
  – Compensating the backlight images
    • Application of the AHMHE
      – Reduction of the process time
      – Preventing color’s purity
        » Due to the overenhancement in bright areas
      – Maintaining high local contrast
    • Application of the chroma correction
      – Producing vivid and colorful images