Digital Camera Zooming Based on Unified CFA Image Processing Steps

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• Proposal of the resuable, low-complexity operation to achieve high-quality zoomed output for single-sensor digital camera
  • Compact and low-cost single-sensor solutions often lack optical zooming capabilities and thus depends on digital techniques
  • Computational power required for high-quality output using traditional techniques is generally too prohibitive to implement in such devices
  • High-level system components are color filter array(CFA) zooming, CFA interpolation(demosaicking) and demosaicked image postprocessing.

Fig.1. A single-sensor architecture
Introduction

- The single-sensor camera is embedded in the mobile phone
- Zooming functionality is usually augmented using digital interpolation after demosaicking of Bayer pattern image into full color image
  - Amplifying the lack of sharpness and false color artifacts present in demosaicked image
  - Requiring the computational and memory of full color interpolation
    - Making it prohibitive for hardware implementation

Fig. 2. Bayer patterns
The introduction of a cost-effective digital zooming solution for single-sensor digital camera

- Three steps: CFA zooming, CFA interpolation (demosaicking), and demosaicked image post-processing
- Utilizing the local color ratio and edge-sensing weight coefficient in each above sub-procedure, resulting in cost-effective hardware implementation
  - Local color ratio is to reduce output color artifacts
  - Edge-sensing mechanism is to track varying image statistics
- $K_1 \times K_2$ Bayer CFA image

\[
b_{(m,n)} = \begin{cases} 
(b_{(m,n)1}, 0, 0) & \text{for (odd } m, \text{ even } n), \\
(0, 0, b_{(m,n)3}) & \text{for (even } m, \text{ odd } n), \\
(0, b_{(m,n)2}, 0) & \text{otherwise.}
\end{cases}
\]

Where $(m, n)$ denotes spatial position $b_{(m,n)k}:$ available color component for $k = 1, 2, 3$
− Unified camera image processing system
  • CFA zooming
    ◆ Generate a higher resolution Bayer CFA image from the original CFA
  • CFA interpolation
    ◆ Generate a full color image from the higher resolution CFA image
  • Post-processing
    ◆ Reduce distracting artifacts and enhancing the sharpness in final output

− Key point of the unified system
  • Implementation of only a small number of basic, low-complexity operation
  • Execution of the CFA zooming before demosaicking
A. CFA Zooming

Principle of the Bayer data zooming

- Original CFA data should be assigned unique position which correspond to the Bayer pattern of an enlarged image

\[ \lambda_K \times \lambda_K \text{ Bayer image} \]

\[
\begin{align*}
    x_{(2m-1,2n)} &= b_{(m,n)} \quad \text{for (odd } m, \text{ even } n) \\
    x_{(2m,2n-1)} &= b_{(m,n)} \quad \text{for (even } m, \text{ odd } n) \\
    x_{(2m-1,2n-1)} &\quad \text{otherwise}
\end{align*}
\]

where \( b_{(m,n)} \): original CFA image

\( X \): zoomed image

\( (m,n) \): coordinate in original CFA image
Missing G component $x_{(r,s)2}$

- Weighted sum of the surrounding original G components $x_{(r,s)2}$

$$x_{(r,s)2} = \sum_{(i,j) \in \xi} w_{(i,j)} x_{(i,j)2}$$

$$\xi = \{(r - 2, s), (r, s - 2), (r, s + 2), (r + 2, s)\}$$

$$w_{(i,j)} = u_{(i,j)} / \sum_{(g,h) \in \xi} u_{(g,h)}$$

- Positive edge-sensing coefficients

$$u_{(i,j)} = \frac{1}{1 + \sum_{(g,h) \in \xi} \left| x_{(i,j)k} - x_{(g,h)k} \right|}$$

1. Denominator: Absolute difference between the CFA input located at $(i,j)$ and the rest of the CFA inputs describe by $\xi$

2. Preserving edge features by detecting the trend of the surrounding components
◆ Remaining missing G component
  • Incorporating two original G components and two interpolated G components from the previous step

\[
X_{(r,s)} = \sum_{(i,j) \in \zeta} W_{(i,j)} X_{(i,j)2}
\]

\[
W_{(i,j)} = \frac{u_{(i,j)}}{\sum_{(g,h) \in \zeta} u_{(g,h)}}
\]

\[
\zeta = \{(r-1,s-1), (r-1,s+1), (r+1,s-1), (r+1,s+1)\}
\]

\[
u_{(i,j)} = \frac{1}{1 + \sum_{(g,h) \in \zeta} \left| X_{(i,j)k} - X_{(g,h)k} \right|}
\]
Constitution of the missing R components

- The missing R(or B) component at the center of the surrounding structure is estimated using the surrounding local color ratio(LCR) and G component adjacent to the center.

**LCR** is defined as (R/G, B/G)

\[
x_{(r,s)} = x_{(r,s-1)} + \sum_{(i,j) \in \zeta} w_{(i,j)} \{ x_{(i,j)} / x_{(i,j-1)} \}
\]

\[
\zeta = \{(r-2,s-2),(r-2,s+2),(r+2,s-2),(r+2,s+2)\}
\]

\[
R(r,s) = G(r,s-1).
\]

\[
\begin{align*}
R(r,s-2) & \quad G(r-2,s-3) \\
R(r+2,s-2) & \quad G(r+2,s-3)
\end{align*}
\]

\[
\begin{align*}
w_{r-2,s-2} & \quad R(r-2,s-2) + w_{r-2,s+2} R(r-2,s+2) \\
w_{r+2,s-2} & \quad R(r+2,s-2) + w_{r+2,s+2} R(r+2,s+2)
\end{align*}
\]
Remaining missing R

- Same as the previous method except with the diamond-shaped structure of both original and interpolated R components location

\[
x_{(r,s)1} = x_{(r,s-1)2} \sum_{(i,j) \in \zeta} w_{i,j} \left\{ x_{(i,j)1} / x_{(i,j-1)2} \right\}
\]

\[
\zeta = \{(r-2,s), (r, s-2), (r, s+2), (r+2, s)\}
\]
Constitution of the missing B components

- G components is positioned on unit downward
B. CFA interpolation

- Estimating the missing R and B color components utilizing the weighting and LCR model same as previous CFA zooming step

\[ x_{(r,s)} = \sum_{(i,j) \in \zeta} W_{(i,j)} x_{(i,j)} \]

\[ \zeta = \{(r - 1, s), (r, s - 1), (r, s + 1), (r + 1, s)\} \]

\[ W_{(i,j)} = \frac{u_{(i,j)}}{\sum_{(g,h) \in \zeta} u_{(g,h)}} \]

\[ u_{(i,j)} = \frac{1}{1 + \sum_{(g,h) \in \zeta} \left| x_{(i,j)k} - x_{(g,h)k} \right|} \]
Interpolation of the R and B component

- LCR is generated using G components in the same spatial position as the R or B

\[
x_{(r,s)k} = x_{(r,s)2} \sum_{(i,j) \in \zeta} w_{(i,j)} \{x_{(i,j)k} / x_{(i,j)2}\}
\]

\[
\zeta = \{(r-1,s-1),(r-1,s+1),(r+1,s-1),(r+1,s+1)\}
\]
C. Post-processing

- Employing the post-processing to reduce false color artifacts and enhance sharpness
  - Taking advantage of the underlying Bayer pattern present before the CFA interpolation
  - Iterative update of the components estimated during CFA interpolation

- Update of the G-components estimated during CFA interpolation using an LCR

\[
x_{(r,s)2} = x_{(r,s)k} \sum_{(i,j) \in \zeta} W_{(i,j)} \left\{ \frac{x_{(i,j)2}}{x_{(i,j)k}} \right\}
\]

\((r,s)\) : position which corresponds to Bayer pattern R(or B)

\(\zeta = \{(r-1,s), (r,s-1), (r,s+1), (r+1,s)\}\)
Update of the R and B components estimated during CFA interpolation

- First, updating R components on Bayer pattern B location and B component on Bayer pattern R location with previous updated G

\[ x_{(r,s)k} = x_{(r,s)2} \sum_{(i,j) \in \zeta} w_{(i,j)} \left\{ x_{(i,j)k} / x_{(i,j)2} \right\} \]

- Second, updating remaining locations with estimated R or B component
1. Original CFA components filled into the zoomed CFA image according to (2), as shown in Fig. 3a.
2. Interpolate the missing G component according to (3) with \( \zeta = \{(r - 2, s), (r, s - 2), (r, s + 2), (r + 2, s)\} \) (Fig. 3a)
3. Interpolate the missing G component according to (3) with \( \zeta = \{(r - 1, s - 1), (r - 1, s + 1), (r + 1, s - 1), (r + 1, s + 1)\} \) (Fig. 3b)
4. Interpolate the missing R and B components using (6) and (7), respectively, with \( \zeta = \{(r - 2, s - 2), (r - 2, s + 2), (r + 2, s - 2), (r + 2, s + 2)\} \) (Fig. 3c and Fig. 3e)
5. Interpolate the missing R and B components using (6) and (7), respectively, with \( \zeta = \{(r - 2, s), (r, s - 2), (r, s + 2), (r + 2, s)\} \) (Fig. 3d and Fig. 3f)
6. Interpolate the missing G component according to (3) with \( \zeta = \{(r - 1, s), (r, s - 1), (r, s + 1), (r + 1, s)\} \) (Fig. 3h)
7. Interpolate the missing R and B components using (8) with \( \zeta = \{(r - 1, s - 1), (r - 1, s + 1), (r + 1, s - 1), (r + 1, s + 1)\} \) (Fig. 3i and Fig. 3j)
8. Interpolate the missing R and B components using (8) with \( \zeta = \{(r - 1, s), (r, s - 1), (r, s + 1), (r + 1, s)\} \) (Fig. 3k and Fig. 3l)
9. Correct the interpolated G component according to (9) with \( \zeta = \{(r - 1, s), (r, s - 1), (r, s + 1), (r + 1, s)\} \) (Fig. 3h)
10. Correct the interpolated R and B components using (8) with \( \zeta = \{(r - 1, s - 1), (r - 1, s + 1), (r + 1, s - 1), (r + 1, s + 1)\} \) (Fig. 3i and Fig. 3j)
11. Correct the interpolated R and B components using (8) with \( \zeta = \{(r - 1, s), (r, s - 1), (r, s + 1), (r + 1, s)\} \) (Fig. 3k and Fig. 3l)

A \( K_1 \times K_2 \) enlarged, full color camera output \( x(l) \)
Test image is captured using three-sensors cameras or color scanner

**Bayer pattern**

- The original color image ($\lambda K_1 \times \lambda K_2$) is down-sampled to $K_1 \times K_2$ and sampled with Bayer pattern to obtain the test pattern.
Conventional method

- CIZ: bilinear CFA interpolation followed by bilinear image zooming in the RGB color domain
- LZ: CFA zooming followed by bilinear CFA interpolation
- CDES: color-difference edge-sensing CFA zooming

Evaluation

- MAD (mean absolute error), MSE (mean square error), NCD (normalized color difference criterion)
### Objective evaluation

#### TABLE I
**Comparison of the methods using the test image Mountains**

<table>
<thead>
<tr>
<th>Method</th>
<th>MAE</th>
<th>MSE</th>
<th>NCD</th>
</tr>
</thead>
<tbody>
<tr>
<td>CIZ</td>
<td>10.939</td>
<td>317.0</td>
<td>0.1701</td>
</tr>
<tr>
<td>LZ</td>
<td>11.688</td>
<td>362.7</td>
<td>0.1849</td>
</tr>
<tr>
<td>CDES</td>
<td>10.478</td>
<td>283.2</td>
<td>0.1879</td>
</tr>
<tr>
<td>Proposed unified scheme</td>
<td>10.276</td>
<td>264.2</td>
<td>0.1681</td>
</tr>
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#### TABLE II
**Comparison of the methods using the test image Window**

<table>
<thead>
<tr>
<th>Method</th>
<th>MAE</th>
<th>MSE</th>
<th>NCD</th>
</tr>
</thead>
<tbody>
<tr>
<td>CIZ</td>
<td>7.233</td>
<td>155.2</td>
<td>0.0703</td>
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<tr>
<td>LZ</td>
<td>8.288</td>
<td>204.1</td>
<td>0.0908</td>
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<tr>
<td>CDES</td>
<td>6.149</td>
<td>113.4</td>
<td>0.0805</td>
</tr>
<tr>
<td>Proposed unified scheme</td>
<td>5.982</td>
<td>104.1</td>
<td>0.0675</td>
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#### TABLE III
**Comparison of the methods using the test image Girls**

<table>
<thead>
<tr>
<th>Method</th>
<th>MAE</th>
<th>MSE</th>
<th>NCD</th>
</tr>
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<tr>
<td>CIZ</td>
<td>5.839</td>
<td>132.4</td>
<td>0.0730</td>
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<tr>
<td>LZ</td>
<td>6.923</td>
<td>183.2</td>
<td>0.0903</td>
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<tr>
<td>CDES</td>
<td>5.074</td>
<td>100.9</td>
<td>0.0815</td>
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<tr>
<td>Proposed unified scheme</td>
<td>5.191</td>
<td>96.1</td>
<td>0.0764</td>
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#### TABLE IV
**Comparison of the methods using the test image Mask**

<table>
<thead>
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<th>Method</th>
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<th>NCD</th>
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</thead>
<tbody>
<tr>
<td>CIZ</td>
<td>16.344</td>
<td>623.5</td>
<td>0.1669</td>
</tr>
<tr>
<td>LZ</td>
<td>17.736</td>
<td>737.2</td>
<td>0.1879</td>
</tr>
<tr>
<td>CDES</td>
<td>14.499</td>
<td>513.6</td>
<td>0.1768</td>
</tr>
<tr>
<td>Proposed unified scheme</td>
<td>14.050</td>
<td>463.9</td>
<td>0.1449</td>
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#### TABLE V
**Comparison of the methods using the test image Lighthouse**

<table>
<thead>
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<th>Method</th>
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<th>MSE</th>
<th>NCD</th>
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<tbody>
<tr>
<td>CIZ</td>
<td>9.516</td>
<td>318.7</td>
<td>0.0762</td>
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<tr>
<td>LZ</td>
<td>10.143</td>
<td>362.9</td>
<td>0.0850</td>
</tr>
<tr>
<td>CDES</td>
<td>9.118</td>
<td>300.2</td>
<td>0.0674</td>
</tr>
<tr>
<td>Proposed unified scheme</td>
<td>9.008</td>
<td>284.8</td>
<td>0.0578</td>
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#### TABLE VI
**Comparison of the methods using the test image Parrots**

<table>
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<th>Method</th>
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<th>NCD</th>
</tr>
</thead>
<tbody>
<tr>
<td>CIZ</td>
<td>4.983</td>
<td>127.6</td>
<td>0.0374</td>
</tr>
<tr>
<td>LZ</td>
<td>5.819</td>
<td>158.9</td>
<td>0.0481</td>
</tr>
<tr>
<td>CDES</td>
<td>4.608</td>
<td>104.4</td>
<td>0.0413</td>
</tr>
<tr>
<td>Proposed unified scheme</td>
<td>4.579</td>
<td>93.2</td>
<td>0.0371</td>
</tr>
</tbody>
</table>
Subjective evaluation

- Sharper details and reduction of artifacts present along high-contrast edges
(a) Original image

(b) CIZ scheme

(c) LZ scheme

(d) CDES scheme

(e) Proposed scheme
Conclusion

- A unified camera image processing system that performs zooming and full color image reconstruction on Bayer pattern image
  - Utilizing a small number of low-complexity operation for efficient hardware implementation
  - Achieving high quality output without amplification of distracting artifacts