Subpixel arrangements and color image rendering methods for multiprimary displays

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Abstract

◆ New subpixel architecture
  – Two new hexagonal subpixel architectures optimized for multiprimary color displays
  – Useful to eliminate the color fringe artifact
  – Better visual quality than previous three primary color architectures including the RGB stripe architecture

◆ New image rendering method
  – Using the method with and without subpixel rendering
Introduction

◆ Color fringe error
  – RGB stripe (the way to arrange these subpixels)
    • A pattern of square-shaped pixels with three vertical subpixels of the same size

Fig. 1. RGB stripe.
– **Subpixel rendering**

  • **Concept**

    
    | R | G | B | R | G | B |
    |---|---|---|---|---|---|
    | R | G | B | R | G | B |

    < pixel>

    The same driving value of the same location

  • **Method**

    – True type letters represented in an analogous way such as curves or functions described simply by numbers

  • **Advantages**

    – More accurate depiction of their silhouettes
    – Increasing the horizontal resolution three times
Defect
  • Bring color fringe error (CFE) in the black text on white background
    – Vertical lines, tilted lines, and rotationally symmetric figures
  • Definition of the measure of CFE
    • Applied target
      – The display of any object filled with foreground color on any background color
    • Definition
      \[
      M_{CFE} = \sum_{a \in A} \min(d_{fg}, d_{bg})
      \] (1)
      where
      - \( A \) is the subpixel rendered object
      - \( a \) is a unit area, e.g., 1 pixel
      - \( d_{fg} \) is the chromaticity distance the possible chromaticities of the unit area a ant the foreground color
      - \( d_{bg} \) is a similar distance for the background color
Fig. 2. Symbolic visualization of CFE in CIE $u'$, $v'$ uniform color space. In this example, a red color object (open dot) is displayed on a nearly achromatic background (filled dot). Due to the improper subpixel rendering, unexpected blue color (filled triangle) appears at the edge of the object. Here, the chromaticity difference between the background color and the unexpected color ($d_{bg}$) is decisive in terms of Eq. (1).
Fig. 3. Theoretical appearance (small letters) and real photos (large letters) of a bold Times New Roman type letter m displayed on a commercial RGB-stripe-based LCD screen with subpixel rendering (left) and without subpixel rendering (right).
Color gamut
- Using a better arrangement of the multiprimary subpixels
  - Better image quality and an extended color gamut

Fig. 4. Enlargement of the color gamut of a multiprimary system compared to a classical three-primary system, in the CIE $u'$, $v'$ chromaticity diagram. Chromaticities of the display primaries are at the nodes of the hexagon or the triangle.
Recent three-primary subpixel architectures and rendering methods

◆ Two main research directions
  – Software algorithm for the RGB stripe architecture
    • Enhancing the horizontal resolution of fonts
      – Increasing the readability of small letters at the cost of some color errors
    • Main idea (ClearType)
      – Mapping mathematical description of fonts on the level of subpixels
        » Minimization of the color error caused by the rendering of luminance information, at a subpixel level
  – Development of architecture of different layouts and their color image rendering methods
Principles for the designing of subpixel arrangements

◆ Minimal CFE
  – Occurring case
    • The border of black characters over a white background
      – Neighboring color pixels
        » Cyan-red for g-b-r and blue-yellow for b-r-g in the Fig.3
  – Terms of settlement
    • Positioning the subpixels in an altering way
      – No neighboring of the same primary colors can arise
      – Such as checkerboard
Modulation transfer function (MTF)

- A high MTF stands for good display resolution
- Definition
  - A curve representing the ratio of the output and input contrast as a function of line frequency

$$MTF(\nu) = \frac{M_o}{M_i}$$

where $M_0$ and $M_i$ indicate the modulation (contrast) of the output and input images of a square-wave grating (altering black and white lines) of line frequency $\nu$

$$M = \frac{(L_{\text{max}} - L_{\text{min}})}{(L_{\text{max}} + L_{\text{min}})}$$

where $L_{\text{max}}$ and $L_{\text{min}}$ are the maximum and minimum luminance of grating

- RGB stripe subpixel architecture
  - Impossible to generate very thin lines of any otherwise displayable color including white or gray
◆ Isotropy
  – Definition
    • Directional independence of the subpixel architecture
  – Not working in vertical direction (RGB-stripe)
    • Not well displaying titles lines and calligraphic letters
  – Another design principle (from 3.1~3.3)
    • Possible to draw thin and long rectangular stripes not only vertically and horizontally, but in any direction
    • The summation of the color of the crossed subpixels yield any color within color gamut, including gray and white
      – Within thin lines
◆ Luminance resolution
  – Placing the blue pixels in a sparser manner
    • Relatively low spatial resolution of short wavelength sensitive receptors
  – Larger than any other subpixels for blue subpixel
    • To reach the proper display white point
    • Not exhibiting high luminance
      – Visually dividing the architecture and blocking the visually uniform blending of the light out
      – Evoking visible textures in the areas which look homogeneous
  – Terms of settlement
    • Using more blue pixels of normal size (same size and number as the other pixels) and in the couples of the same address
    • Luminance channel that carries the finest spatial detail
High aperture ratio

- Minimizing the area for wiring or other electronics components where there is no emitted light
- Terms of settlement
  - Covering the plane completely
    - Triangles, rectangles, and hexagons
  - Being a stochastic pattern
New multiprimary architectures

- **First architecture**
  - \( P_1, P_3 \) and \( P_5 \) : Red, green, and blue
  - \( P_2, P_4 \) and \( P_6 \) : Yellow, cyan, and magenta

Fig. 5. Six-primary architecture for subpixel rendering: left, original arrangement; right, original arrangement rotated by 30 deg counterclockwise
Second architecture

- \(P_1, P_2, P_3, P_4, P_5, \text{and } P_6\) : Identical to the first architecture
- \(P_7\) : White

Fig. 6. Six-primary architecture for subpixel rendering: top, arrangement of the primary colors; bottom, a sequence of subpixels taken from the architecture. This is the thinnest possible horizontal line containing all primary colors.
Table 1. Comparison of the hexagonal architectures and the RGB stripe layout

<table>
<thead>
<tr>
<th></th>
<th>RGB Stripe</th>
<th>Hexagon (6 prim.)</th>
<th>Hexagon (7 prim.)</th>
<th>Hexagon (6 prim. rotated)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of subpixels</td>
<td>324</td>
<td>300</td>
<td>304</td>
<td>312</td>
</tr>
<tr>
<td>MTF vertical</td>
<td>6</td>
<td>7.5</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>MTF horizontal</td>
<td>4.5</td>
<td>3.5</td>
<td>8</td>
<td>6.</td>
</tr>
<tr>
<td>Vertical addressability</td>
<td>12</td>
<td>15</td>
<td>36</td>
<td>25</td>
</tr>
<tr>
<td>Horizontal addressability</td>
<td>9</td>
<td>18</td>
<td>16</td>
<td>12</td>
</tr>
</tbody>
</table>

Table 2. A sample CFE calculation

<table>
<thead>
<tr>
<th>Arch.</th>
<th>Font</th>
<th>Total number of Subpixels</th>
<th>1 r</th>
<th>2 g</th>
<th>3 b</th>
<th>4 c</th>
<th>5 m</th>
<th>6 y</th>
<th>7 w</th>
<th>Mean</th>
<th>STD (CFE)</th>
<th>Max. dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>RGB stripe</td>
<td>Arial</td>
<td>80</td>
<td>26.3</td>
<td>27.5</td>
<td>46.3</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>33.3</td>
<td>11.2</td>
<td>12.9</td>
</tr>
<tr>
<td></td>
<td>Times</td>
<td>77</td>
<td>28.6</td>
<td>27.3</td>
<td>44.2</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>33.3</td>
<td>9.4</td>
<td>10.8</td>
</tr>
<tr>
<td>Six-prim.</td>
<td>Arial</td>
<td>73</td>
<td>19.2</td>
<td>19.2</td>
<td>15.1</td>
<td>15.1</td>
<td>15.1</td>
<td>16.4</td>
<td>—</td>
<td>15.7</td>
<td>2.0</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>Times</td>
<td>63</td>
<td>17.5</td>
<td>15.9</td>
<td>17.5</td>
<td>15.9</td>
<td>15.9</td>
<td>17.5</td>
<td>—</td>
<td>15.7</td>
<td>0.9</td>
<td>0.8</td>
</tr>
<tr>
<td>Seven-prim.</td>
<td>Arial</td>
<td>88</td>
<td>14.8</td>
<td>13.6</td>
<td>14.8</td>
<td>13.6</td>
<td>14.8</td>
<td>13.6</td>
<td>14.8</td>
<td>14.3</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>Times</td>
<td>53</td>
<td>15.1</td>
<td>11.3</td>
<td>15.1</td>
<td>15.1</td>
<td>17.0</td>
<td>11.3</td>
<td>14.3</td>
<td>14.3</td>
<td>2.1</td>
<td>3.0</td>
</tr>
<tr>
<td>Six-prim. rotated</td>
<td>Arial</td>
<td>83</td>
<td>15.7</td>
<td>16.9</td>
<td>15.7</td>
<td>18.1</td>
<td>18.1</td>
<td>15.7</td>
<td>—</td>
<td>15.7</td>
<td>1.2</td>
<td>1.4</td>
</tr>
<tr>
<td></td>
<td>Times</td>
<td>67</td>
<td>14.9</td>
<td>13.4</td>
<td>16.4</td>
<td>19.4</td>
<td>19.4</td>
<td>16.4</td>
<td>—</td>
<td>15.7</td>
<td>2.4</td>
<td>3.2</td>
</tr>
</tbody>
</table>
Fig. 7. Subpixel rendered black Arial and Times New Roman letters n on a white background. Arial letters are in the first row and Times New Roman letters in the second row. Architectures: first column, original continuous image; second column, RGB stripe; third column, six-primary; forth column, seven-primary; and fifth column, six-primary rotated.
Color image rendering method for the multiprimary arrangements

◆ Method
  – Input
    • Luminance at the level of subpixels and the whole color information at the level of whole (logical) pixels
  – $C_i$
    • Denoting the relative driving value or weight of subpixel $P_i$ in a pixel
    • Interval of \([0,1]\)
    • $i$ is the index of the primaries
  – Problem of multiprimary color image rendering
    • Decomposition of a three dimensional input vector $XYZ$ is not straightforward
      – Not \((3 \times n)\) matrix and invertible
Case for n=6, rendering the color of any arbitrary original input tristimulus value $XYZ_{\text{orig}}$

- Dividing the six color primaries of the pixel into two $\{P_1, P_2, P_3\}$ and $\{P_4, P_5, P_6\}$
- Changing the drive values of the first group ($C_i, i = 1, 2, 3$)
- Calculating the corresponding XYZ output in every optimization by summing up the output of the first group
- Calculating remainder $XYZ_{\text{rem}}$
  - Difference between the input color $XYZ_{\text{orig}}$ and the current value of $XYZ$
- Rendering $XYZ_{\text{rem}}$ in the 3-D space of relative driving values of the second group of $\{P_4, P_5, P_6\}$
  - Using a linear matrix transform
- Out-of-gamut error \((i = 4, 5, 6)\)

\[
E_{\text{col}} = \sum \Delta_i
\]

where

\[
\Delta_i = 0 \text{ if } C_i \in [0, 1],
\]

\[
\Delta_i = -C_i \text{ if } C_i < 0, \text{ and}
\]

\[
\Delta_i = C_i - 1 \text{ if } C_i > 1, \text{ for } i = 4, 5, 6
\]

- For first group, weights are changed \((C_i, i = 1, 2, 3)\)

  - Reducing \(E_{\text{col}} = \sum \Delta_i\) until \(E_{\text{col}} = \sum \Delta_i\) is minimal

\[
w_{\min}(0) = 0.5, \quad (3)
\]

\[
w_j(n) = w_{\min}(n - 1) + \frac{(j - 3)(1/3)^{n-1}}{6}
\]

where \(w = C_1, C_2, C_3\) and \(j = 0, 1, \ldots, 6\)

\[
XYZ_{\text{sum}} = C_{1_i} \cdot XYZ_1 + C_{2_j} \cdot XYZ_2 + C_{3_k} \cdot XYZ_3
\]

where \(w_j = C_{1_i}, C_{2_j}, C_{3_k}\)

\[
XYZ_{\text{rem}} = XYZ_{\text{orig}} - XYZ_{\text{sum}}
\]
Subpixel luminance error term

- Difference
  - the luminance ratios of the subpixels within a logical pixel (denoting $Y_i/Y_i$)
  - Same luminance ratios in the original image (denoting $Y_{i0}/Y_{i0}$)

\[
E_{\text{lum}} = \sum_i \left( \frac{Y_i}{Y_1} - \frac{Y_{i0}}{Y_{10}} \right), \quad i = 2, \ldots, 6
\]  \hspace{1cm} (4)

- Total error function

\[
E_{\text{tot}} = \alpha E_{\text{col}} + \beta E_{\text{lum}}
\]  \hspace{1cm} (5)

where $\alpha$ and $\beta$ are suitable weight parameters
Conclusion

◆ Purposed method
  – Formulating design principles
    • Eliminating the color fringe error through new multiprimary pixel architecture
    • Better visual quality
    • Seven-primary system seems a better choice
    • Key point of the optimal number of primaries
  – New image rendering method
    • Definition of error function
    • Enabling proper chromaticity reproduction and enhancing luminance resolution
    • Revealing the proper balance between optimizing the chromaticity error and luminance reproduction