Characterization of Multicolor Printing: Challenges and Solutions

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Characterization of a printing process

“What is the color of an ink combination?”

- Ink combination = tone values per ink, 0–100 %
- Color = CIELAB values

Standard method:

- Calibrate the printing process
- **Print and measure a test chart**
- Make a profile

There are standard test charts for CMYK (IT 8.7/4).
What should we use **for multicolor printing**?
How to design a multicolor test chart

Maybe do it as for CMYK, just extend to more inks... so:

- Historic review: ideas behind CMYK test charts
- Additional aspects for more than 4 inks
- What about existing multicolor test charts?
  - e.g. ColorBlind, Monaco Profiler, Profile Maker, Esko Equinox, Argyll

Goal: to create a **test chart for 7 inks**
History of CMYK test charts

1. CMY is most important – use a **complete grid** (e.g. 5x5x5)
   - K is simple, just use a separate wedge (PO 135, GMG TC3)
   - Requires some model to add the effect of black on CMY.

2. Help the model by guiding “**black lines**”:
   - Add increasing K to a few CMY combinations (PM3 TC2.9, PO 210)

3. Higher precision is needed for GCR and UCR separations:
   - Use “**black planes**” with complete CMY grids (CB, GMG TC4, MP).

4. Gradations are captured with **detailed wedges** (IT8.7/3, PM3 TC6.02).

Automated devices impose a practical limit of 1 page (Letter/A4),
the standard IT8.7/4 test chart has 1617 patches.
### The IT8.7/4 standard CMYK test chart (ISO12642)

**Grid structure of the IT8.7/4:** *(some other grids omitted)*

<table>
<thead>
<tr>
<th>K levels</th>
<th>CMY grid steps</th>
<th>number</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0 10 20 30 40 55 70 85 100</td>
<td>9×9×9</td>
</tr>
<tr>
<td>20</td>
<td>0 10 20 40 70 100</td>
<td>6×6×6</td>
</tr>
<tr>
<td>40, 60</td>
<td>0 20 40 70 100</td>
<td>5×5×5</td>
</tr>
<tr>
<td>80</td>
<td>0 40 70 100</td>
<td>4×4×4</td>
</tr>
<tr>
<td>100</td>
<td>0 40 100</td>
<td>3×3×3</td>
</tr>
</tbody>
</table>

- **Single-ink wedges every 5%** *(plus 2, 3, 7, and 98%)*

- **CMY gray balance patches at the same K levels**
  
  5, 3, 3 – 10, 6, 6 – 20, 12, 12 – 40, 27, 27 – 60, 45, 45 – 80, 65, 65 – 100, 85, 85

- **Note how higher K levels have CMY grids which are subsets,**
  which isolates the effect of K at constant CMY *(like black lines)*

  *(Most other test charts redistribute the CMY steps freely)*
Multicolor test charts

We explore the field of multicolor test charts.

- General aspects: combinatorics
- Printing aspects: amount of ink, available screens for halftoning
- The expanded color gamut (ECG) use case:
  Using traditional CMYK process inks and OGV (or red/blue).
  The extra inks can increase gamut size and hue stability in separations

Existing solutions have made use of some of these aspects, but not all of them.
The curse of dimensionality

- Naive intention: uniform sampling of press behavior
- Start by treating all inks with equal rights, ignore reduction by K levels for now
- In IT8.7/4, the CMY resolution is 10–15% (9 steps).
- For 4 inks, 9 steps lead to $9^4 = 6561$ patches.
- For 7 inks, this amounts to $9^7 \approx 5$ million patches.
- Even with only 4 steps, we have $4^7 = 16384$ patches at a rather poor resolution of 33%.
- How can we reduce this set of patches to 1000–5000? (1–4 pages)
Saving patches: by a TAC limit

- We usually cannot print $7 \times 100\%$ ink.
- Device space is the unit hypercube $[0, 100\%]^n$.
- A TAC limit $L$ means ink sum $\sum x_i \leq L$. This is a plane $\perp$ to the main diagonal.
- The volume of the hypercube is cut by the plane.
- By symmetry, cutting at half point (half TAC) removes the darker half of the patches.
  (not exact for discrete steps due to quantization)
- A TAC of 350 $\%$ is helpful and often just printable.
  For 7 inks and 4 steps, $16384 \rightarrow 8192$ patches. We still need less.
Saving patches: by less overprinting inks (“opis”)

- Less overprinting inks mean less color variation.
  4 opis are sufficient (like CMYK). This reduces TAC too.

- For $s$ steps per ink excluding 0, and up to $m$ overprints,
  the number of patches for $n$ inks is $\sum_{i=0}^{m} \binom{n}{i} s^i$

- For 7 inks, 4 steps ($s=3$) and 4 opis ($m=4$): 3991 patches.

- Küppers used only 3 opis: YOK, OMK, MVK, VCK, CGK, GYK
  Boll* used 4 opis: GYOK, YOMK, OMVK, MVCK, VCGK, CGYK
  Current separations also use 4 opis: YOMK, MVCK or MVCY, CGYK

* Harold Boll (Kodak), Proc. SPIE 2170, 1994, p. 108ff
AM halftoning causes screen clash for ink pairs with same raster parameters (typically C+O, M+G, K+V).

Such overprints are very sensitive to register variations (differences can easily reach 20 ΔE).

C+O and M+G are not used in separations.

K+V can occur but are also problematic.

Remove all patches which contain such pairs: 1372 patches.

We might also remove O+G, G+V, V+O: 832 patches.
IDEAlliance ECG test chart project (led by Ron Ellis)

- Propose a standard ECG test chart (7c, CMYKOGV)
- Should be supported by all major profile vendors
  (active: Alwan, ColorLogic, Esko, GMG, Heidelberg, Kodak, ...)
- Should be suitable for offset, flexo, gravure, digital printing
- Should provide a reasonable CMYK characterization too

- Verify performance of current version 4 by test prints:
  Fuji FinalProof, 3 Offset Prints, 1 Flexo Print
- Used in the Fogra Multicolor Event (October 2018)
What seems important for a common chart?

- Most profile vendors prefer regular grids
- CMYK is still most important (as basis for separation)
- All color combinations should be covered (e.g. also O+G)
- Black still gets special treatment (less grid steps at higher K)
- Most vendors require a subset of grids at higher K
- In most use cases, screen exclusion rules apply (no C+O, M+G)
- Result should be a patch list, not a fixed chart layout
- Available space is usually 4 pages, at most
Current version: ECG v4, ingredients

- 4-step 7c grid: CMYOGV 0,40,70,100 and K 0,40,80,100
  (up to 4 overprinting inks, reduced steps at 100 K)
- 6-step CMYK grid: CMY 0,20,40,70,85,100 and K 0,20,40,60,80,100
  (reduced CMY steps at higher K)
- CMY near-gray wedges at 0,10,20,30,40,55,70,85,100
  (plus grid neighbors around this wedge)
- Single-ink wedges: 15 steps per ink
- Fogra multicolor media wedge 7c
- 2-step 7c grid: 0,40 (not 100)
  (up to 7 overprinting inks, can lead to screen clashes)
Current version: ECG v4

- Example layout by GMG, 4 pages, $35 \times 30$ patches, ink limit 400 %
- Suitable for many devices, meets i1iO2 requirements for scan mode
- First page alone is meant to provide reasonable quality, supplemental pages can be used to improve quality
- Pages 1–3 have repeated single-ink wedges (can check print variation)
- Page 4 has repeated overprints of 40 % (can check print variation)
Description of pages

1. page 1: basic 7c grid, CMY grid at K=0, wedges, CMY gray at K=0,40,80
2. page 2: more 7c, CMY grids at K=20,40,80,100
3. page 3: more 7c, CMY grids and near-neutral patches
4. page 4: more 7c, CMY grid at K=60, overall rather dark

Patch counts:

<table>
<thead>
<tr>
<th>page</th>
<th>with ECG</th>
<th>CMYK only</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>(opis)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>608</td>
<td>442</td>
<td>105</td>
<td>201</td>
<td>444</td>
<td>289</td>
<td>0</td>
<td>7</td>
<td>1</td>
<td></td>
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<tr>
<td>2</td>
<td>811</td>
<td>239</td>
<td>105</td>
<td>60</td>
<td>547</td>
<td>316</td>
<td>21</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>675</td>
<td>375</td>
<td>105</td>
<td>63</td>
<td>392</td>
<td>488</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>914</td>
<td>136</td>
<td>7</td>
<td>27</td>
<td>128</td>
<td>879</td>
<td>6</td>
<td>1</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>
Verification charts

- “Centers” testchart, two pages. Similar to a body-centered cubic grid.
  At the centers of the grid cells, interpolation error is maximal. E.g., for 7c, 0,20,55,85 is centered in 0,40,70,100.

- “Random” (by ColorLogic and Kodak) contains extra high-ink and non-grid patches

Patch counts:

<table>
<thead>
<tr>
<th>page</th>
<th>with ECG</th>
<th>CMYK only</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>(opis)</th>
</tr>
</thead>
<tbody>
<tr>
<td>c1</td>
<td>494</td>
<td>556</td>
<td>106</td>
<td>143</td>
<td>638</td>
<td>162</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>c2</td>
<td>526</td>
<td>524</td>
<td>9</td>
<td>166</td>
<td>715</td>
<td>160</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>r1</td>
<td>955</td>
<td>95</td>
<td>133</td>
<td>91</td>
<td>119</td>
<td>184</td>
<td>454</td>
<td>66</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>
Experiments

- ECG v4 test chart: 4 pages, cumulative, grid 0-40-70-100 (K 80)
- Centers test chart: 2 pages, later also Random test chart
- Fuji: FinalProof GXT (transfer laminate), C=O, M=G=B
- Fogra/MAN Roland: Offset KCMYBOG, C=O, M=G, K=B (only ECG v4)
- Offset 2: KCMYOGV, C=O, M=G, V FM (no Random)
- Offset 3: KCGOVMY, C=O, M=G, V FM (also Random)
- Flexo 1: YOMGVCK, on BOPP matte white film (but problems)

Results are shown for the offset prints.
Measured data: duplicate patches, single ink wedges

- Same ink wedges on ECG p1, p2, p3, Centers page c1, Random page r1
- For single inks, 1–2 $\Delta E_{00}$ on avg must be expected
- Often, midtones vary more than solids
Measured data: duplicate patches, overprints

- Duplicates of 40% overprints of 2–4 inks from p1 are on p4 and c1, some on r1.
- For overprints, an average uncertainty of >2 $\Delta E_{00}$ must be expected.

<table>
<thead>
<tr>
<th>$Q_{50}$</th>
<th>$Q_{95}$</th>
<th>N</th>
<th>pair</th>
<th>print</th>
<th>inks</th>
<th>screens</th>
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</thead>
<tbody>
<tr>
<td>2.5</td>
<td>5.5</td>
<td>52</td>
<td>p4-p1-op</td>
<td>Fogra</td>
<td>KCMYBOG C=O, M=G, K=B</td>
<td></td>
</tr>
<tr>
<td>2.1</td>
<td>3.7</td>
<td>35</td>
<td>c1-p3-op</td>
<td>Offset 2</td>
<td>KCMYOGV C=O, M=G, V FM</td>
<td></td>
</tr>
<tr>
<td>2.4</td>
<td>5.2</td>
<td>52</td>
<td>p4-p1-op</td>
<td>Offset 3</td>
<td>KCGOVMY C=O, M=G, V FM</td>
<td></td>
</tr>
<tr>
<td>2.2</td>
<td>4.1</td>
<td>35</td>
<td>c1-p3-op</td>
<td>Offset 3</td>
<td>KCGOVMY C=O, M=G, V FM</td>
<td></td>
</tr>
<tr>
<td>1.8</td>
<td>4.5</td>
<td>52</td>
<td>p4-p1-op</td>
<td>Offset 3</td>
<td>KCGOVMY C=O, M=G, V FM</td>
<td></td>
</tr>
<tr>
<td>2.4</td>
<td>5.1</td>
<td>20</td>
<td>p2-r1-op</td>
<td>Offset 3</td>
<td>KCGOVMY C=O, M=G, V FM</td>
<td></td>
</tr>
<tr>
<td>2.4</td>
<td>5.1</td>
<td>20</td>
<td>p2-r1-op</td>
<td>Offset 3</td>
<td>KCGOVMY C=O, M=G, V FM</td>
<td></td>
</tr>
<tr>
<td>4.3</td>
<td>6.4</td>
<td>18</td>
<td>p3-r1-op</td>
<td>Offset 3</td>
<td>KCGOVMY C=O, M=G, V FM</td>
<td></td>
</tr>
<tr>
<td>5.9</td>
<td>6.6</td>
<td>18</td>
<td>c1-r1-op</td>
<td>Offset 3</td>
<td>KCGOVMY C=O, M=G, V FM</td>
<td></td>
</tr>
<tr>
<td>1.9</td>
<td>4.2</td>
<td>19</td>
<td>c2-r1-op</td>
<td>Offset 3</td>
<td>KCGOVMY C=O, M=G, V FM</td>
<td></td>
</tr>
</tbody>
</table>

$\Delta E_{00}$ percentiles
GMG OpenColor

Process-based modeling:
- Describe the mosaic of overprinting dots deposited on a substrate, with ink trapping
- Model details depend on process (offset, flexo, rotogravure, . . .)
- Model parameters have a physical correspondence

Testing procedure:
- Use GMG OpenColor to create a profile from a subset (e.g. page 1)
- For the rest of the data, compare measurement to profile output.
Results: model uses pages 1–4 (full characterization)

ECG v4 pages 1–4 (complete testchart) fed into OpenColor (averages duplicates)

Profile is compared to data from all chart pages

Result for Centers is more interpolation error, for Random it is also prediction error
Results: model uses pages 1–3

ECG v4 pages 1–3 (skipping dark page p4) fed into OpenColor

Same quality for Centers

Dark p4 colors and some dark colors from Random get less accurate

Still better than expected printing variation!
Results: model uses pages 1 and 2

ECG v4 pages 1+2 fed into OpenColor

Still same for Centers

pages 3+4 and Random get less accurate

Still better than expected printing variation!
Results: model uses only page 1

Only first page fed into OpenColor

Gradation is now only representative for page 1

Depending of ink zones and test form layout, other pages get worse
Stepping back a little — what have we found?

- With a full characterization (pages 1–4), the model results for the remaining pages are around $2 \Delta E_{00}$ on average.
- With less data (only page 1), errors for the 2-page “Centers” are still unchanged. Errors for the dark charts (page 4 and “Random”) are higher.
- However, those patches are less relevant for image separations.

- But does it mean that a full characterization is better? More truthful to the average press result? What is the ground truth to compare against?

- The data have shown printing variations. They contain patches with screen clashes. Can we get rid of that?
Results: model uses only page 1 (repeated)

Only first page fed into OpenColor

Gradation is now only representative for page 1

Depending of ink zones and test form layout, other pages get worse
Results: no screen clash

Only first page fed into OpenColor

Compare only to data without screen clash

Note how errors are significantly lower
Results: no screen clash + pages linearized

Pages 1–3 are **linearized** to the same average single ink gradations.

Only first page fed into OpenColor

Compare only to data without screen clash

Note how errors are again slightly reduced

<table>
<thead>
<tr>
<th>Pages</th>
<th>Overprints</th>
<th>ΔE00 avg</th>
<th>Fogra-p1</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 adj</td>
<td>n=105</td>
<td>1.2</td>
<td>0.9</td>
</tr>
<tr>
<td>2 adj</td>
<td>n=105</td>
<td>1.7</td>
<td>1.3</td>
</tr>
<tr>
<td>3 adj</td>
<td>n=105</td>
<td>1.9</td>
<td>1.8</td>
</tr>
<tr>
<td>4 adj</td>
<td>n=7</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Adj</td>
<td>n=115</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td>Adj</td>
<td>n=133</td>
<td>1.9</td>
<td>1.9</td>
</tr>
</tbody>
</table>

**Centers-page12**

<table>
<thead>
<tr>
<th>Pages</th>
<th>Overprints</th>
<th>ΔE00 avg</th>
<th>Fogra-p1</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 adj</td>
<td>n=105</td>
<td>1.2</td>
<td>0.9</td>
</tr>
<tr>
<td>2 adj</td>
<td>n=105</td>
<td>1.7</td>
<td>1.3</td>
</tr>
<tr>
<td>3 adj</td>
<td>n=105</td>
<td>1.9</td>
<td>1.8</td>
</tr>
<tr>
<td>4 adj</td>
<td>n=7</td>
<td>2.0</td>
<td>2.0</td>
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<tr>
<td>Adj</td>
<td>n=115</td>
<td>1.1</td>
<td>1.1</td>
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<tr>
<td>Adj</td>
<td>n=133</td>
<td>1.9</td>
<td>1.9</td>
</tr>
</tbody>
</table>

**Random-adj**

<table>
<thead>
<tr>
<th>Pages</th>
<th>Overprints</th>
<th>ΔE00 avg</th>
<th>Fogra-p1</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 adj</td>
<td>n=105</td>
<td>1.2</td>
<td>0.9</td>
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<tr>
<td>Adj</td>
<td>n=133</td>
<td>1.9</td>
<td>1.9</td>
</tr>
</tbody>
</table>
Results: only single inks, no screen clash + pages linearized

Pages 1–3 are linearized to the same average single ink gradations.

Only the average single-ink wedges are fed into OpenColor

Compare only to data without screen clash

Errors are still not far from expected printing variation
**Results: using 5 steps per ink, no screen clash, pages linearized**

Pages 1–3 are linearized to the same average single ink gradations.

Use only 20, 40, 70, 85, 100% (7×5 + 1 = **36 patches**)

Compare only to data without screen clash

Errors increase only slightly

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**Experiments**

**Measured data**

**Results: OpenColor model**

**Summary**
Results: using 3 steps per ink, no screen clash, pages linearized

Pages 1–3 are linearized to the same average single ink gradations.

Use only 40,70,100% (7×3 + 1 = 22 patches) like a print control strip

Compare only to data without screen clash

Errors increase only slightly
Summary

- A flexible multi-vendor multi-process ECG test chart was created
- Page 1 covers the regular ECG use case (without screen clash) quite well
- **Printing variations** must be taken into account (roughly, average $\Delta E_{00} > 2$)

**GMG OpenColor can predict to a similar accuracy** (shown for offset)

- **Even from mini-strip test charts** (down to print control strips)
  – which gives a very consistent, smooth profile, no bumps!
  (Of course, having some overprints is better than no ink-ink interaction.)

- To get representative data from a test print, better use a small chart multiple times than many pages.
Thanks for your attention.