Process Control and Color Management Implementation

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ABSTRACT

ICC color management technology can be adopted in a number of workflows. Unfortunately, not all color-management systems, as implemented, achieve equal success in real world. There are a number of factors that limit color management performance. This paper reviews factors such as end user’s expectations and color management limitations. However, the objective of this paper is to discuss device limitations and how to use statistics and process control methodology to assess and reduce these variations. Test targets, color measurement, and press sheet sampling are utilized to assess spatial uniformity as well as temporal consistency of hard copy output devices. By comparing temporal variation of the process against specifications, process capability indices, CP and Cpk, are used to analyze run-to-run color repeatability. To enhance color management performance, a demerit system, based on amplitude responses, was used to determine the best press sheet for printer profiling application. Color management performance ultimately depends on our ability to minimize and control spatial, temporal, and run-to-run variations.

Keywords: ICC, color management, process control, statistics

1. INTRODUCTION

When printing from the same digital file, we can easily observe color variations among different output devices. This phenomenon depicts the device nature of color imaging. In order to achieve consistent color across imaging devices, color management performs two tasks: (1) assign a color definition to digital values in a device color space, and (2) preserve the color by converting digital values from one color definition to the other.

The color management task of assigning a color definition to an imaging device is by means of profiling. The task of converting digital images from a source device to its destination is modeled in Figure 1. The source profile provides the link between the input device color space and the profile connection space (PCS). The destination profile provides the link between the PCS and the output device color space. The color management module (CMM) takes the two profiles to accomplish the conversion in an application programming interface (API), such as Adobe Photoshop.

![Figure 1. Color management model.](image)

2. COLOR MANAGEMENT LIMITATIONS

There are a number of factors that limit real world color management performance. We can divide these factors into three categories: end user’s expectations, profile limitations, and device limitations. We will briefly review end user’s expectations and profile limitations. The main objective of this paper is to discuss device limitations and how to use statistics and process control techniques to assess and minimize device variations.

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2.1 End user's expectations

There are two objectives in color image reproduction: producing pleasing color images and matching a color image. If the end user is a consumer of the printed product, then pleasing color image is what matters. If the end user, e.g., art director, ad agency, takes ownership of the image, then matching proofs and press sheets closely, if not exactly, becomes critical. In other words, there are differences in end user's expectations between a scan-to-print workflow and a proof-to-print workflow. While color management may serve pleasing color image reproduction well, it may not succeed in delivering close color match, as expected, between proofs and press sheets.

2.2 Profile limitations

If there is a unique color for every CMYK combination at one percent increment, then the total number of colors a CMYK output device can produce is equal to \((100 \times 100 \times 100 \times 100)\) or 100 million colors. We realize that with these many colors two unique color codes do not necessarily produce noticeable color difference between them. In fact, human eye can only distinguish about two million colors under good visual color matching conditions (Nickerson and Newhall, 1943). Nevertheless, let's take this as an example and examine the process of profile construction.

A profiling target can only cover a limited set of possible device signals. For example, the number of color patches in a printer profiling target is around 1,000 (not two millions or more). This is an extremely small percentage in comparison to the entire color signals that are sent to an output device. When color behavior of an output device are not properly sampled by these color patches, profile accuracy will suffer.

A profile is only accurate as the measurements on which it's based. A color measurement device and its colorimetric conditions, i.e., geometry, illuminant, observer, are variables that contribute to variations in constructing an output profile. Graphic arts technology standards, e.g., CGATS.5, ISO 12647, are useful in standardizing measurement practices, but there are still unresolved issues, e.g., aperture size and measurement backing, that can cause variation.

A profile can only cover a small subset of the entire device signals. The limited number of grid points that make up the look-up tables cannot account for non-linearity of the device in various regions of the device color space. As a result, interpolation and rounding errors will result during color conversion.

2.3 Device limitations

Printed colors are subject to the following device variations: (1) the degree of spatial uniformity or within-sheet variations; (2) the degree of temporal consistency or sheet-to-sheet variations; and (3) the degree of color repeatability or run-to-run variations. If these device-related variations are unknown and unaccountable, it further impedes the color management performance. We shall take a closer look at these device-related variations in the following section.

3. COLOR MANAGEMENT AND PROCESS CONTROL

Color management is the process of making diverse imaging devices working together to achieve color consistency. In a larger context, process control is optimization and calibration of all devices that serve color management needs (Figure 2). Device profiles can only be accurate to the degree that devices are optimized and calibrated during routine usage.

![Figure 2. Process control as a prerequisite to color management.](image-url)
3.1 Device optimization

Device optimization should precede device calibration. Optimization is to determine the compatibility among hardware, software, and consumables (colorants and substrate) at the device level. Gray scales, densitometers, resolution targets, and visual assessment are used in the optimization process. For example, there is no need to build a profile for an inkjet printer unless the substrate, printer addressability, and color gamut are optimized. Relative to a computer-to-plate (CTP) technology, device optimization often includes a compromise between exposure and plate life. When printing frequency modulated (FM) screening, device optimization focuses on the ability to print micro dots via exposure and addressability. In other words, there is little value to build a profile under sub-optimized or unknown conditions. Once optimum device conditions are determined, they provide the baseline for calibration.

3.2 Device calibration

Device calibration must precede device profiling. Device calibration is the act of changing a device’s behavior so that its amplitude responses, e.g., density as a function of digital value, conform to known values. Here, known values may be determined from within the device itself, e.g., the maximum gamut of an inkjet device. Alternatively, known values may represent a widely accepted printing standard, e.g., SWOP. When a proofing device is calibrated to have the same amplitude responses, colorants, and substrate as the press, color is managed without profiles.

4. ASSESSING DEVICE VARIATIONS

Once the device is optimized, calibrated, and profiled, what’s left in process control is to track and to compensate for device drifts. Like the game of curling played on ice, press make-ready is launching the process (stone) towards its target. Like sweeping actions in curling, process control focuses on the efforts of guiding and correcting the process over the course of print production. In this instance, we want to minimize variations by removing assignable-caused variations. Before we can minimize device variations, we need to know what are these variations, and how to measure them.

4.1 Spatial (within-sheet) variation

When we measure anything once, we learn nothing about variation. Variation refers to how close the measurements compare to one another. In spot color printing, we can assess spatial variation by (1) making multiple measurements over the color of interest, (2) find the average of all measurements, (3) find the average deviation as the estimate of within-sheet variation.

The above method would not work for process color printing because there are many colors and tonal values. In order to assess spatial (within-sheet) variation of process color printing, we can measure two identical IT8.7/3 basic targets (182 color patches) that are placed at different locations in two orientations on the press sheet (Figure 3).

![IT8.7/3 basic target in two orientations](image-url)

Figure 3. IT8.7/3 basic target in two orientations.
Color difference between two patches can be measured colorimetrically and expressed in ΔE unit. For example, the color difference in patch B13 will be small because this is the patch with no ink printed. Color differences in other CMYK patches will be large. Color differences between the two IT8.7/3 targets can be expressed as a cumulative relative frequency (CRF) of ΔE (Chung and Shimamura, 2001). Figure 4 shows the within-sheet variation as a ΔE distribution for a web offset printed sheet. For this example, there is little or no perceived color difference between the two targets. However, the larger the median ΔE and maximum ΔE are, the more within-sheet variation the printing process possesses. This, in turn, makes the profile less accurate.

![Figure 4. A cumulative relative frequency of ΔE distribution.](image)

4.2 Temporal (sheet-to-sheet) variation

To study temporal consistency of a process at a given location, a minimum of 30 samples are considered reasonable. By means of press sheet sampling and measurements, we can observe the temporal variation of the process in terms of a process performance chart. Figure 5 illustrates the temporal variation of a web offset press for solid ink density. Notice that data are plotted as deviations from aim points with tolerances indicated as dotted lines. The graph suggests that all four printers have temporal variations. In addition, some magenta solid ink densities are outside of the upper specification limit (USL).

![Figure 5. Solid ink density performance chart.](image)

Figure 6 shows the temporal variation of the same web offset press for midtone dot gain. The dot gain consistency is plotted as the deviation from aim points. We can tell that the black dot gain is overall too low and the cyan dot gain is overall too high.
4.3 Run-to-run variation

While a graph is worth a thousand words, a performance chart does not provide a specific quantity to sum up the temporal variation within a press run. This would make the assessment of run-to-run variation next to impossible. To quantify the capability of a process by a simple index, we adopted the methodology from ISO/TC69, Process Capability and Performance Measures (ISO/TC69, 1997). Process capability index, CP, is the ratio of tolerance over 6σ (Equation 1). The higher the CP, the more consistent the process is.

\[
CP = \frac{\text{Tolerance}}{6\sigma} = \frac{\text{USL} - \text{LSL}}{6\sigma} \quad \text{(Eq. 1)}
\]

Process consistency, CP, does not address process accuracy. We can identify the process deviation in terms of the difference between the average of measurements and the aim point. Process accuracy, CpK, is defined as either the ratio between the difference between the upper specification limit (USL) and the average, divided by 3σ; or the difference between the average and the lower specification limit (LSL), divided by 3σ, whichever the quantity is smaller (Equation 2).

\[
\text{CpK} = \text{Lesser of} \frac{\text{USL} - \text{Mean}}{3\sigma} \quad \text{or} \quad \frac{\text{Mean} - \text{LSL}}{3\sigma} \quad \text{(Eq. 2)}
\]

CpK is more important than CP because it addresses both accuracy and precision. The higher the CpK, the more repeatable and accurate the process is. A process with a CpK of 1.33 is desired. When CpK indices of 1.33 or higher are achievable time after time, we can conclude that the process is repeatable.

4.4 CP and CpK interpretation

CP and CpK of solid ink densities of a web offset press are shown in Table 1. There are a number of interpretations of CP and CpK for process control: (1) The yellow printer is most consistent (CP = 1.52) and accurate (CpK = 1.26) in solid ink density; (2) the black printer is least consistent (CP = 0.91) in solid ink density; (3) the magenta printer is not accurate (CpK = 0.01). In general, it is easier to improve process accuracy by adjusting the deviation and harder to reduce variation.
Table 1. Solid ink density summary.

<table>
<thead>
<tr>
<th></th>
<th>Dv</th>
<th>Dr</th>
<th>Dg</th>
<th>Db</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(K)</td>
<td>(C)</td>
<td>(M)</td>
<td>(Y)</td>
</tr>
<tr>
<td>Aim point</td>
<td>1.60</td>
<td>1.30</td>
<td>1.40</td>
<td>1.00</td>
</tr>
<tr>
<td>Average</td>
<td>1.57</td>
<td>1.30</td>
<td>1.50</td>
<td>1.02</td>
</tr>
<tr>
<td>Max</td>
<td>1.68</td>
<td>1.35</td>
<td>1.57</td>
<td>1.06</td>
</tr>
<tr>
<td>Min</td>
<td>1.48</td>
<td>1.24</td>
<td>1.44</td>
<td>0.95</td>
</tr>
<tr>
<td>Range</td>
<td>0.20</td>
<td>0.11</td>
<td>0.13</td>
<td>0.11</td>
</tr>
<tr>
<td>σ</td>
<td>0.04</td>
<td>0.03</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td>CP</td>
<td>0.91</td>
<td>1.13</td>
<td>0.99</td>
<td>1.52</td>
</tr>
<tr>
<td>CPK</td>
<td>0.62</td>
<td>1.13</td>
<td>0.01</td>
<td>1.26</td>
</tr>
</tbody>
</table>

CP and Cpk of dot gains of a web offset press are shown in Table 2. While all four printers require more accuracy in dot gain conformance, the yellow printer, having a high CP of 1.76, shows the best potential in achieving process accuracy. Adjusting dot gain (or gradation) with the use of a one-dimensional transfer curve in the RIP usually provides a reasonable solution.

Table 2. Dot gain summary.

<table>
<thead>
<tr>
<th></th>
<th>Dv</th>
<th>Dr</th>
<th>Dg</th>
<th>Db</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(K)</td>
<td>(C)</td>
<td>(M)</td>
<td>(Y)</td>
</tr>
<tr>
<td>Aim point</td>
<td>22</td>
<td>20</td>
<td>20</td>
<td>18</td>
</tr>
<tr>
<td>Average</td>
<td>20.01</td>
<td>22.68</td>
<td>20.58</td>
<td>17.53</td>
</tr>
<tr>
<td>Max</td>
<td>24.40</td>
<td>26.65</td>
<td>28.74</td>
<td>22.17</td>
</tr>
<tr>
<td>Min</td>
<td>16.46</td>
<td>20.30</td>
<td>18.38</td>
<td>16.49</td>
</tr>
<tr>
<td>Range</td>
<td>7.93</td>
<td>6.35</td>
<td>10.35</td>
<td>5.68</td>
</tr>
<tr>
<td>σ</td>
<td>1.52</td>
<td>1.24</td>
<td>1.56</td>
<td>0.85</td>
</tr>
<tr>
<td>CP</td>
<td>0.99</td>
<td>1.21</td>
<td>0.96</td>
<td>1.76</td>
</tr>
<tr>
<td>CPK</td>
<td>0.22</td>
<td>0.89</td>
<td>0.77</td>
<td>0.99</td>
</tr>
</tbody>
</table>

5. PROCESS CONTROL AND COLOR MANAGEMENT IMPLEMENTATION

Process control is a critical factor in color management implementation. There are three areas that process control will have a positive impact on color management performance, i.e., selecting the best sheet for profiling, identifying process performance gaps, and seeking process improvement.

5.1 Best sheet selection

Most color management software requires one sample (or no more than three samples) to generate a device profile. When 30 or more press sheets have been measured to determine its process capability, we have many samples to choose from. Ideally, we don’t want to measure all sampled sheets, but measure the press sheet that conform to specifications the closest. Therefore, a very interesting question arises, "Which press sheet conforms to specifications the closest?"

To answer the question, we define the best sheet as a sampled press sheet with no visual flaws and with its amplitude responses conform to the specifications the closest. Visual flaws over a large flat tints is a qualitative indication of spatial variation. Mis-match of pictorial images is a qualitative indication of amplitude variation. To determine the best sheet quantitatively, we compute the sum of deviations of midtone dot gain, solid ink densities for all four CMYK channels. We also include the midtone spread (Equation 3) as a part of the total demerit (ISO 12647-1, 1996). In other words, the best sheet has the smallest demerit among all samples. We found this method of determining the best sheet for profiling to be objective and effective.

\[
\text{Spread} = \max \left[(A_c - A_{c0}), (A_m - A_{m0}), (A_y - A_{y0})\right] \\
- \min \left[(A_c - A_{c0}), (A_m - A_{m0}), (A_y - A_{y0})\right] \\
\text{(Eq. 3)}
\]

- \(A_x\) is measured tonal value
- \(A_{x0}\) is specified tonal value
- where x is c, m, and y

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5.2 Improving device performance

Improving device performance begins with assessing its critical parameters and capabilities. For process color printing, the first issue is spatial uniformity; the next is amplitude response of CMYK; and the next is the balance of CMY in midtone areas. To improve spatial uniformity in lithography, we need to pay attention to test form layout, ink starving, ink feed, ink and water balance, etc. To improve spatial uniformity in digital printing, we have very different issues, e.g., relative humidity, temperature, charge decay, toner level, to account for. Likewise, there are unique challenges in maintaining spatial uniformity in flexographic and in gravure printing processes.

The key to improving amplitude responses begins by analyzing sources of demerits. Table 3 provides an example of an amplitude demerit analysis. Notice that a total of 50 press sheets being analyzed. The total demerit is based on three sources of deviation, i.e., dot gain deviation of CMYK, solid ink density deviation of CMYK, and midtone spread deviation of CMYK. While press sheet #43 has the lowest demerit score, the largest demerit comes from the solid ink density deviation. Thus, special efforts, e.g., real-time measurement and corrective action, should be made in subsequent press runs to ensure better solid ink density conformance. By doing so, the device improvement will come.

<table>
<thead>
<tr>
<th>Press Sheet</th>
<th>DG Deviation</th>
<th>STD Deviation</th>
<th>Midtone Spread</th>
<th>Total Demerit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Best Sheet</td>
<td></td>
<td></td>
<td></td>
<td>43</td>
</tr>
<tr>
<td>Start</td>
<td>8.7</td>
<td>18.0</td>
<td>4.2</td>
<td>30.8</td>
</tr>
<tr>
<td>2</td>
<td>5.8</td>
<td>19.0</td>
<td>2.7</td>
<td>27.6</td>
</tr>
<tr>
<td>3</td>
<td>6.9</td>
<td>17.0</td>
<td>2.3</td>
<td>26.2</td>
</tr>
<tr>
<td>4</td>
<td>7.0</td>
<td>23.0</td>
<td>4.9</td>
<td>34.9</td>
</tr>
<tr>
<td>5</td>
<td>7.3</td>
<td>21.0</td>
<td>3.5</td>
<td>31.8</td>
</tr>
<tr>
<td>6</td>
<td>6.0</td>
<td>23.0</td>
<td>2.7</td>
<td>25.7</td>
</tr>
</tbody>
</table>

When the demerit for midtone spread is large, neutrals in pictorial color image reproduction will have color cast. In order to improve gray balance from the device point of view, we need to pay attention to CP and CpK of the process. Taking an impact printing process as an example, if the temporal consistency, CP, of midtone spread is less than 1.0, the mechanics of the press must be examined closely for worn parts. If the temporal consistency, CP, of midtone spread is greater than 1.33, but its CpK is less than 1.0, the most effective method for correcting midtone spread is in the prepress. Applying transfer curves at RIP will reconcile deviations between device responses and the aim points.

6. DISCUSSION

This paper provides a summary of how color management can be realized in a print production environment. Sections of the methodology, e.g., process capabilities, have been explored and tested in the past. However, this paper brings color management under a larger context of process control. Process control focuses on device optimization, use of standard operating procedures, test targets, and measurement technology for device calibration. Process control is different from color management. We need process control in order to make color management work.

A profile is a snapshot of how the device operates under a given condition. Like a traveler who tries to reach to his/her destination, a map can be useful to help him/her to get there. But the map can be misleading if the terrain has changed. There is also the possibility that a wrong map is used. In many ways, process control provides a means for verifying if the device color behavior stay the same or not. If the device color behavior had altered, then the decision is needed to either bring the device back to its original state, or a new profile should be constructed.
7. CONCLUSION
The reason that we implement color management technology is because it has the potential in meeting or exceeding end user’s color imaging expectations. To realize the potential, this paper emphasizes the need to analyze device variations quantitatively. Device variations, in terms of spatial, temporal, and run-to-run variations are introduced. Minimizing these variations with the use of statistics and process know-how are discussed. Color management performance ultimately depends on our ability to analyzing and minimizing device variations. And that's the essence of process control.

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REFERENCES