Construction Features of Color Output Device Profiles

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Abstract

Software developers have created applications that can build custom device profiles that conform to the standards established by the International Color Consortium (ICC). These software applications must address several color reproduction issues during the construction of an ICC device profile. The color reproduction issues could be controlled by input from the person building the profile or by predetermined algorithms. Collecting input from the profile builder requires specific features in the user interface of the software application. The challenge for the software developer is the trade-off between full featured controls to satisfy the needs of an expert profile builder and limited controls to provide ease of use for a novice profile builder.

Introduction

The International Color Consortium has developed specifications for device profiles for both monochrome and color devices.[1] There are three basic classifications or types of profiles: input, display, and output. In addition, there are four special types of profiles: device link, color space conversion, abstract, and named color. The focus of this paper is the construction of output device profiles for CMYK color printing.

The ICC specifications for color output device profiles primarily address the elements of the profile that are necessary to make the profile functional and compatible. Some of the elements in the profile contain numeric look-up tables (LUTs) for transforming data. The ICC specifications cover the format of the LUTs, but not the algorithms by which they are constructed. The construction of these LUTs can be very complex and remains as a proprietary component of profile construction software.

It will be shown that there are many color reproduction issues that need to be addressed in a color transformation and that these issues must be solved within the construction of color output device profiles. Profile construction software developers are faced with the challenge of providing the profile builder with enough control over the color reproduction issues without overwhelming them with complex decisions. A recommendation is made for three levels of feature sets based on necessary, desired, and optional controls.

ICC Specifications

Output device profiles for color devices have several required tags. The tags are the individual elements of the profile. The following tags are required for RGB, CMY, and CMYK output profiles.[2]

1. profileDescriptionTag
2. AToB0Tag
3. BToA0Tag
4. gamutTag
5. AToB1Tag
6. BToA1Tag
7. AToB2Tag
8. BToA2Tag
9. mediaWhitePointTag
10. copyrightTag

The AToB and BToA tags are the fundamental elements of the profile. Each of these six tags contains information that is needed for a color transformation. The name of the tag indicates the type of color transformation for which the tag should be used. For example, the AToB0Tag should be used for A-to-B conversions with the perceptual rendering intent. The "A" designates the device dependent color space and the "B" designates the device independent color space, also known as the Profile Connection Space (PCS). The rendering intent is designated by the 0, 1, or 2. These rendering intents are:

0: Perceptual
1: Relative Colorimetric
2: Saturation

There is a fourth rendering intent that is supported by the ICC, but it does not require a separate tag. This is the Absolute Colorimetric rendering intent and it is implemented through a set of equations, the data in the media WhitePointTag, and the data in the AToB1Tag or BToA1-Tag.

Each of the AToB and BToA tags contains a 3×3 matrix and several LUTs. The data processing sequence within each of these tags is:

1. 3×3 matrix
2. non-interdependent per-channel tone reproduction one-dimensional LUTs
3. multidimensional LUT

4. non-interdependent per-channel linearization one-dimensional LUTs

The 3×3 matrix is mandated to be an identity matrix unless the input to the matrix is in the XYZ color space. Therefore, if neither the A or B space is the XYZ color space, then the 3×3 matrix is an identity matrix and can be ignored.

For CMYK color printing, the A space is the CMYK color space.

The ICC specification allows three options for the B space (i.e., PCS):

- 8 bit CIELAB data
- 16 bit CIELAB data
- 16 bit CIEXYZ data

For CMYK color printing, the PCS is usually 8 bit CIELAB or 16 bit CIELAB.

ICC Workflow

There are several color reproduction issues that need to be addressed in a color transformation. The transformation work-flow adopted by the ICC uses a Color Management Module (CMM) and device profiles. The CMM is primarily a data processing engine and relies on the data within the device profiles for translating digital color data from one color space to another color space. Therefore, the color reproduction issues must be satisfied within the contents of the device profiles.

The specific set of color reproduction issues depends on whether the output device profile is used as the source or destination profile in a color transformation. When the output device profile is used as a source profile, the CMM uses the AToB tags for the color conversion in the A to B direction (i.e., device color space to PCS). When the output device profile is used as a destination profile, the CMM uses the BToA tags for the color conversion in the B to A direction (i.e., PCS to device color space). The bi-directional capabilities of output device profiles enables a few workflow options (e.g., RGB-to-CMYK, CMYK-to-RGB, and CMYK-to-CMYK).

Fundamental Assumptions

The properties of the substrate and the colorants are the start-ing point for any discussion of color reproduction in a printing process. The standards organizations for traditional printing processes (e.g., offset lithography) have recognized substrates and colorants as the starting point for establishing standards for a printing process.[3] The properties of the substrate and the colorants are equally important to color reproduction with non-impact printing processes.

The method by which color output device profiles are constructed inherently incorporates the properties of the substrate and the colorants in the construction of the profile tags. The profile construction process begins with a digital file of a target image and a print made from this file. The digital data is a stimulus and the printed target image is the response. A comparison of the stimulus and the response produces a characterization of the system. The response of the system is quantified by measurements of the printed target image with a colorimeter or spectrophotometer. These measurements inherently contain information about the properties of the substrate, the colorants, and their interactions. As a result, there is no need for control over the properties of the substrate or colorants in the user interface of profile construction software.

B-to-A Color Reproduction

For conversions from PCS to device color space (i.e., CIELAB to CMYK), the list of color reproduction issues can be derived primarily from high-end color separation systems for the graphic arts. Although these color separation systems convert RGB scanner signals to CMYK halftone tints, the objectives are similar.

Some of the color reproduction issues in the conversion from PCS to device color space are options that have been enabled by digital image processing technology and were not derived from traditional color separation systems.

The color reproduction issues for conversions from PCS to device color space are:

1. rendering intent
2. gamut mapping
3. appearance modeling
4. gray component replacement (GCR)
5. total area coverage
6. tone compression
7. gray balance ratio
8. maximum colorant amount for each colorant channel
9. minimum colorant amount for each colorant channel
10. amplitude response curve for each colorant channel

The rendering intent of an image is a general description of the intended appearance of colors within the image when rendered in the destination color space. The ICC supports four rendering intents: Absolute Colorimetric, Relative Colorimetric, Perceptual, and Saturation. With four rendering intents supported in one output profile, the ICC has enabled a simple but limited control that will allow profile users to alter the color rendering of an image to account for different image types. Although the ICC supports four rendering intents, it does not require different results from each rendering intent. The ICC specifications allow the profile builder to provide one, two, three, or four results for the four different rendering intents. This allows the profile builder to reduce the file size of the output profile by having multiple tags reference the same data. Therefore, control over the results of the B-to-A rendering intents is a desired feature for profile construction soft-ware.

Gamut mapping is related to rendering intents, but it should be treated as a separate issue. Two of the ICC rendering intents, Absolute Colorimetric and Relative Colorimetric, have specific criteria that constrain the gamut mapping to clipping nonreproducible colors to the gamut surface. The other two ICC rendering intents, Perceptual and Saturation, can have many valid gamut mapping methods. There has been substantial research on gamut mapping methods and these studies have produced general recommendations for specific types of images.[4,5,6,7] The general recommendations can serve as default gamut mapping methods, but they may not satisfy everyone. Therefore, control over the gamut mapping methods is a desired feature for profile construction software.

Appearance modeling addresses the perceptual phenomena that can influence the visual match between two colors. Applying an appearance model to color data can improve the accuracy of communicating the color data through the PCS and mapping the color data for a perceptual rendering intent. Appearance modeling is enabled in an output profile by the use of CIELAB as the PCS.[8] Although CIELAB was not intended as an appearance model, it does contain a von Kries-type of adaptation of the XYZ tristimulus values. There are limitations to the CIELAB color space and other appearance models may be desirable.[9,10,11] A different appearance model could be applied to the data that is used to build the output profile (i.e., device characterization data). Either CIELAB or CIEXYZ could still be used as the PCS. Application of an appearance model to the device characterization data requires an advanced understanding of color science. Therefore, inclusion of appearance model controls is a optional feature for profile construction software.

Gray component replacement removes the neutral (i.e., gray) component of a process color and replaces it with the black colorant. GCR is the fundamental algorithm that determines when black is substituted for neutral combinations of cyan, magenta, and yellow colorants. The GCR level can influence the maximum density and the shadow detail in the printed image. There is a wide latitude of acceptable GCR settings and the profile builder should be allowed to control this to satisfy personal preferences. Therefore, control over the GCR setting is a necessary feature for profile construction software.

The total area coverage is the limit on the sum of the halftone tints of all the colorants for each pixel in an image. The acceptable range for the total area coverage is influenced by the GCR setting, the type of colorant, and the type of substrate. In turn, the total area coverage can influence the saturation and density of a printed image. Some printing methods (e.g., offset lithography) have universal standards for total area coverage. Some printing methods do not have universal standards (e.g., electrophotographic printers) and are subject to personal preference. To accommodate standards and personal preference, the profile builder must be allowed to control the total area coverage. Therefore, control over the total area coverage is a necessary feature for profile construction software.

Tone compression addresses the reduction in tonal range from transparency or monitor image sources to printed images when non-colorimetric gamut mapping is used. Tone compression can be applied by mapping the neutral axis of the PCS to the relative density range of the printing system. This compression method would be sufficient as a default to address the fundamental issue of a media change, but control over the tone compression can be useful for content specific issues that will be discussed later in this paper. Therefore, control over the tone compression is a desired feature for profile construction software.

The gray balance ratio of the cyan, magenta, and yellow colorants compensates for an imbalance in their absorption spectra. Achieving the proper gray balance ratio is critical feed-back for process control in color reproduction. Optimization of the gray balance ratio can be automated with system models and device characterization data. Adjusting the gray balance ratio involves complex interactions and requires an advanced understanding of printing, color science, and tone reproduction. Therefore, control over the gray balance is an optional feature for profile construction software.

The maximum colorant amount for each colorant channel is the maximum halftone tint for that colorant. The minimum colorant amount for each colorant channel is the minimum halftone tint for that colorant. These limits prevent tone reproduction problems in the highlight and shadow areas of the image. The optimum levels for the maximum and minimum colorant amount for each colorant channel are related to the type of colorant, the type of substrate, the halftone screen, and the printing system. The optimum levels can be determined from device characterization data. However, in cases that involve remote or distributed printing, these levels may need to conform to a set of specifications. Therefore, control over the maximum and minimum colorant amount for each colorant channel is a desired feature for profile construction software.

The amplitude response curve for each colorant channel encompasses the previous two issues (i.e., maximum colorant amount and minimum colorant amount), but it also addresses the full tone range between the maximum and minimum values. Adjustment of these curves will influence tone reproduction and can compensate for dot gain. Optimization of the amplitude response curves can be automated with system models and device characterization data. Manual adjustment of the amplitude response curves involves complex interactions and requires an advanced understanding of printing, color science, and tone reproduction. Therefore, control over the amplitude response curves is an optional feature for profile construction software.

A-to-B Color Reproduction

For conversions from device color space to PCS (i.e., CMYK to CIELAB), the primary goal is colorimetric accuracy. In general, color distortions should be avoided. However, in some workflow options where the source and destination media are different, color distortions could improve the appearance of the reproduction.

The color reproduction issues for conversions from device color space to PCS are:

1. rendering intent
2. appearance modeling
3. tone expansion
4. chroma expansion

The ICC supports four rendering intents for conversion from device color space to PCS, but these rendering intents can cause confusion. The rendering intents enable the output device profile, when used as a source profile, to apply rendering distortions to the digital data when the destination profile does not have the ability to do this. It also enables a potential problem for exaggerated rendering if both the source and destination profiles alter the digital data to achieve the rendering goals. If the rendering distortions can be applied in the destination profile, then the source profile should not apply rendering distortions and all three tags in the A to B direction (i.e., AToB0Tag, AToB1Tag, and AToB2Tag) should be based on a relative colorimetric rendering algorithm. This is easily done by having the AToB0Tag and AToB2Tag point to the AToB1Tag; and it dramatically reduces the size of the profile. Therefore, control over the results of the A-to-B rendering intents is a desired feature for profile construction software.

As before, appearance modeling is enabled in an output profile by the use of CIELAB as the PCS. Application of an alternate appearance model to the device characterization data requires an advanced understanding of color science. Therefore, inclusion of appearance model controls is an optional feature for profile construction software.

Tone and chroma expansion can be useful for expanding a CMYK color gamut to a larger color gamut (e.g., RGB or Hi-Fi CMYK). However, this should only be done when the characteristics of the device dependent color space of the destination profile are known and non-colorimetric rendering is appropriate. Therefore, control over tone and chroma expansion are optional features for profile construction software.

Content Specific Issues

The two previous sections on color reproduction issues assumed that the digital image was a "good" digital image. This is a basic assumption for a color management system because the goal is color consistency. The aesthetic qualities of an image are a secondary concern that is often neglected by color management systems.[12]

The definition of a good image depends on the objectives of the artist who created the image. There are some general objectives that will produce an image that is pleasing to most people (e.g., maximum tonal range, moderate contrast, no color cast, etc.). However, there are some objectives that involve personal preference and cannot be judged right or wrong. There are also objectives that may not be achieved by the artist and therefore the image is degraded by defects that must be corrected in the reproduction process. Personal preference and defect correction are addressed by content specific issues of color reproduction.

The typical content specific issues are:

1. color cast
2. tonal range
3. contrast
4. color saturation
5. highlight detail
6. shadow detail
7. sharpness

With the exception of sharpness, all of these content specific color reproduction issues could be addressed in the construction of a device profile. The desired effects could be programmed into the tags of the profile in the same way that the previous color reproduction issues are addressed.

In a color transformation workflow there are three places where content specific color reproduction issues can be addressed: before, during, or after the transformation by a CMM and a set of profiles. The specific workflow of a given situation will dictate which of these three options is the best solution.

In most cases, making content specific adjustments to an image is an iterative process. The iterative nature of the work motivates the operator to perform the work in an environment that will facilitate quick results. Building a profile and applying it to an image is generally considered a slow process. Therefore, content specific issues of color reproduction generally are not addressed in profile construction software.

There are some commercial software applications that can edit an existing profile to alter the data in the tags. This process can be faster than building a new profile.

The consequence of including content specific adjustments in an ICC output device profile is that the utility of the profile becomes narrower. If taken to the extreme scenario, each image would have its own output device profile and there could be a loss in productivity associated with managing a large number of output device profiles.

Profile Size

There is one profile parameter that is not specified by the ICC and is not considered a color reproduction issue; but it is a color transformation issue. This parameter is the number of grid points in the one-dimensional and multidimensional LUTs. This is a critical parameter that directly influences the quality of color transformations. It also influences the size of the output device profile in terms of memory requirements.

The input and output spaces for each LUT have a fixed range of values for each channel. Therefore, the sampling frequency of the input and output spaces increases as the number of grid points in the LUT increases. The time required to build the LUT and the memory required to store the LUT also increase as the number of grid points in the LUT increases. Assuming that there is infinite resolution to the accuracy of the values in the LUT determination, then the accuracy of the color transformation increases as the number of grid points in the LUT increases because the potential for errors from interpolation is reduced. In practice, the accuracy of the determination of mul-tidimensional LUT values is limited and once this limit is reached, an increase in grid points will not improve the accuracy of the color transformation.

The number of grid points in a one-dimensional LUT depends on the bit depth of the data in the LUT. The ICC requires 8-bit one-dimensional LUTs to have 256 grid points, but 16-bit one-dimensional LUTs can have any number from a minimum of two up to a maximum of 4096 grid points.

The bit depth is the number of bits per channel for the data stored in a LUT. In the previous discussions, CMYK data is stored in the A space of a B-to-A multidimensional LUT and CIELAB data is stored in the B space of an A-to-B multidi-mensional LUT. For most color printing systems, 8-bit data (i.e., 8 bits per channel) is sufficient for a CMYK color space. Either 8-bit or 16-bit data is allowed by the ICC when CIELAB is used for the PCS (i.e., B space). The 16-bit data provides greater accuracy for quantifying colors, but it comes at the cost of increasing the size of the profile.

Profile Building Software

The are several software application that are commercially available today for building ICC color output device profiles. The list of products includes:

- ColorBlind from Color Solutions Inc.
- ColorSynergy from Candela Ltd.
- PrintOpen ICC from Linotype Hell Co.
- Profile/80 from RIT Research Corporation
- SMPPro from Color Savvy Systems Inc.

The companies that have developed these products have made decisions about the trade-off between a full feature set that gives the profile builder complete control over all aspects of the profile construction and a limited feature set that makes the product easy to use. The feature set of each product is directly related to the target market of profile builders.

Profile Builders

There are a variety of users for software applications that can build custom ICC color output device profiles. Keep in mind that we are separating profile builders from profile users. The authors believe that the profile builders can be grouped into three categories: novice, intermediate, and expert. These three categories represent three different target markets for the software applications. The classification of profile builders into these three categories is based on the knowledge and objectives of the profile builder.

A novice profile builder would be someone who works for a graphic design company such as an advertising or marketing agency. This person would have knowledge about color graphic design in a computer based environment and could create artwork with desktop software applications. In this scenario, the novice profile builder could be responsible for delivering hard copy proofs of the digital artwork and would need to make custom ICC profiles to implement color management.

An intermediate profile builder would be someone who works in an electronic prepress department or is a prepress consultant. This person would be familiar with color reproduction from hands-on experience and possibly from formal education. This person would recognize the terminology of many of the color reproduction issues discussed earlier in this paper and may have an intuitive understanding of how to use the controls that would influence these reproduction issues. In this scenario, the intermediate profile builder could be responsible for implementing a color management workflow for a prepress operation and would need to make custom ICC profiles for use within that workflow.

An expert profile builder would be someone who works in research and development for new products. This person would have a detailed knowledge of color science and color imaging systems. Since the scope of this paper is restricted to output profiles, the new products could be printing equipment or prepress software. In this scenario, the expert profile builder could be responsible for producing default ICC profiles that would ship with the new product.

Table 1. Profile Construction Feature Sets

	Construction Controls for Color Output Device Profiles	Level One	Level Two	Level Three
1	B-to-A rendering intent		Yes	Yes
2	B-to-A gamut mapping		Yes	Yes
3	B-to-A appearance modeling			Yes
4	B-to-A gray component replacement GCR	Yes	Yes	Yes
5	B-to-A total area coverage	Yes	Yes	Yes
6	B-to-A tone compression		Yes	Yes
7	B-to-A gray balance ratio			Yes
8	B-to-A maximum colorant amount for each colorant channel		Yes	Yes
9	B-to-A minimum colorant amount for each colorant channel		Yes	Yes
10	B-to-A amplitude response curve for each colorant channel			Yes
11	B-to-A bit depth in A space			Yes
12	B-to-A number of grid points for one-dimensional LUTs			Yes
13	B-to-A number of grid points for multi-dimensional LUTs		Yes	Yes
14	A-to-B rendering intent		Yes	Yes
15	A-to-B appearance modeling			Yes
16	A-to-B tone expansion			Yes
17	A-to-B chroma expansion			Yes
18	A-to-B bit depth in B space			Yes
19	A-to-B number of grid points for one-dimensional LUTs			Yes
20	A-to-B number of grid points for multi-dimensional LUTs		Yes	Yes

Level One: necessary   Level Two: necessary + desired   Level Three: necessary + desired + optional

Software Feature Sets

The feature set of the controls for the construction of color output device profiles depends on the target market. An expert profile builder would want all the controls that are possible and relevant. An intermediate level profile builder would want a subset of these controls. A novice level profile builder would want few if any of these controls. The authors propose three levels of feature sets in Table 1. These three levels are associated with the novice, intermediate, and expert profile builders.

Level One contains the minimum necessary controls for a novice profile builder. Level Two contains the minimum necessary controls and the desired controls for an intermediate profile builder. Level Three contains the minimum necessary controls, the desired controls, and the optional controls for an expert profile builder.

Conclusions

The ICC specifications pertaining to color output device profiles were outlined and discussed in this paper as a framework for the ICC workflow. There are several color reproduction and color transformation issues that are not identified within the ICC specifications. These issues were identified and described in this paper using ICC terminology to indicate how these issues can be addressed within the ICC format. These issues are listed, in terms of profile construction controls, in Table 1.

It was observed that software developers for profile construction applications must know the objectives and skill level of profile builders in their target market before they can incorporate the appropriate feature set for construction controls. With this in mind, the authors proposed three target markets (novice, intermediate, and expert) and the feature sets for these markets (Level One, Level Two, and Level Three).

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