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Perceptual Uniformity Improvement of Sampling with LCH Based Look-up Tables using iccMAX Profiles

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Abstract

Look-up tables (LUTs) are frequently used in ICC profiles to establish relationships between a Profile Connection Space (e.g. CIELAB) and a device space (e.g. CMYK). The accuracy of an ICC profile is significantly influenced by the sampling method used to populate its LUTs. This paper investigates using polar coordinates for sampling of LUTs in the B2Ax tags of an iccMAX profile to convert from Profile Connection Space to device space. Additionally, a new sampling approach is proposed to achieve better perceptual uniformity of sampling between grid points using adjustment to LCH coordinates. The method uses DIN99d formula and CIEDE2000 color difference equation to sample grid points along C and H* dimensions in a way that the distance between the grid points along these dimensions is much more perceptually uniform. Using such a strategy to build an iccMAX profile improves roundtrip accuracy while keeping the CLUT size unchanged compared to V4 ICC profiles with some cost in application performance.*

Introduction

Look-up tables (LUTs) are frequently used in ICC profiles to establish relationships between device color co-ordinates and those of the Profile Connection Space (PCS) defined by ICC [1]. Three steps are incorporated to apply a LUT in an ICC profile: sampling, look-up and interpolation [2, 3]. Sampling is used to create a LUT by dividing device or standard color space to sub-spaces by grid points. When applying a LUT for a given color, the first step of the look-up is to find the grid points in which the color is embedded and interpolation is then performed to estimate the corresponding transformed color. In order to reduce possible interpolation errors, it is desirable to have perceptual uniformity between grid points, i.e., color differences between the associated color space addresses of neighboring grid points should ideally be equal. This paper focuses on the topic of the LUT sampling approach used to convert PCS colors to device colors (e.g. CMYK) in B2Ax tags of ICC profiles based on the iccMAX specification.

iccMAX is a profile specification for color management systems promoted by the International Color Consortium® (ICC) [4], which can be thought of as an extension to the version 4 (v4) specification [1]. V4 ICC profiles encode fixed color transforms between device color encoding (CMYK/RGB) and PCSs (CIEXYZ/CIELAB) based upon D50 colorimetry with the CIE 1931 Standard 2-degree observer [1]. However, iccMAX provides significant enhancements for defining color transforms and PCSs to meet needs that cannot easily be met with v4 profiles. Some highlighted aspects of iccMAX include: iccMAX allows for much greater flexibility in how transforms are encoded using an arbitrary sequence of processing elements that can include programmable elements; iccMAX provides flexibility in the selection of PCS illuminant and color matching functions; iccMAX extends connection possibilities to include spectrally based PCSs and named multiplex connection spaces (MCSs); and iccMAX provides support for encoding of viewing and illumination angle appearance information.

Perceptual non-uniformity of sampling in CIELAB space

Rohit et al [5] proposed to construct 1D LUTs for CIELAB a* and b* dimensions to improve perceptual uniformity of inverse LUTs in ICC profiles using the CIEDE2000 color difference equation. Experimental results showed that their proposed approach can improve the accuracy of neutral colors compared to uniform sampling method in CIELAB space [6-8]. As shown in Figure 1, color difference distribution is not uniform in the a*-b* plane. The lowest color difference between grid entries for the sampling investigated (about 2.8 CIEDE2000 units for the sampling rate used in their paper) was near the a* and b* axes. This can be explained by the fact that 1D LUTs along a* and b* dimensions were constructed by b* = 0 and a* = 0 respectively. Color difference is gradually higher when moving away from both axes to the middle color zones. In addition, the highest color difference (about 10.0 CIEDE2000 unit) was in the corners where a* = b* and -a* = b* with high chroma. Therefore, the sampling used in this method does not achieve perceptual uniformity across all hues for large chromas using ICC LUTs.

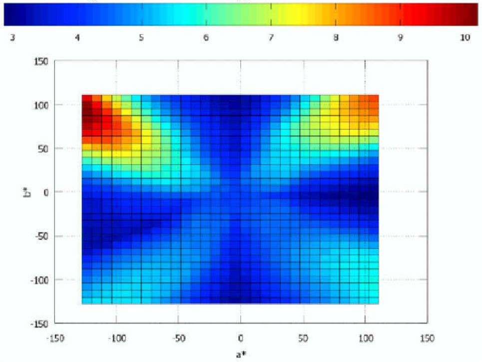

Figure 1 Maximum CIEDE2000 color difference distribution across the a-b* plane with a granularity of 33x33 at constant L* of 50, using the method proposed by Rohit et al [5]*

Perceptual non-uniformity of equal-spaced sampling in CIELCH space

Advanced color difference systems like CMC, CIEDE94, and CIEDE2000 use polar notation (with lightness, chroma, and hue correlates) for determining color differences to better reflect the sensitivity of the human visual system. In this paper we propose using iccMAX to encode the N-dimensional color LUT in a B2Ax tag using lightness, chroma, hue (LCH) addressing in order to improve perceptual uniformity along the hue and chroma directions. For investigational purposes we considered using 20 chroma and 61 hue grid points to equal-spaced sample chroma and hue in the CIELCH space, as shown in Figure 2 where filled colored dots represent grid points. The chroma covers the range of

0 to 181 to completely contain the equivalent a* and b* values in the range of -128 to 127 which are the values defined in an ICC profile. Note that this provides for a larger encoding range for PCS values in the LUT.

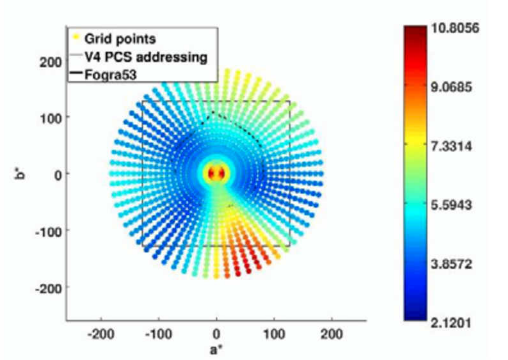

Figure 2. Maximum CIEDE2000 color difference distribution of equal-spaced sampling in the CIELCH space with a granularity of 20x61at constant L of 50, where filled colored dots represent sampled grid points.*

Figure 2 illustrates the distribution of maximum CIEDE2000 color difference of equal-spaced sampling in CIELCH space. For each grid point, the CIEDE2000 color differences compared against its eight neighbors were calculated and the maximum was determined for each point. These maximum differences were then plotted as colors for each grid point. The color blue indicates the lowest CIEDE2000 value of about 2.1 and the color brown indicates the highest CIEDE2000 value of 10.8. The black rectangle represents colors addressable by the CIELAB PCS encoding of v4 ICC profiles. As can be seen in Figure 2, the distribution of color difference is not uniform across the CIELCH grid points constructed using this equal-spaced sampling method. The differences are much higher for colors with small chroma and for blue and purple colors with large chroma.

Improving perceptual uniformity in CIELCH space

Our proposed profile encoding method makes use of an iccMAX calculator element [4] to convert CIELAB to CIELCH and adjust chroma and hue values to provide improved perceptual uniformity of the sampling space over that used for CIELAB sampling methods.

The iccMAX calculator element [11] is a processing element that can be used in a multiProcessElementsType B2Ax tag. The calculator element allows for the encoding of arbitrary functions as a sequence of stack-based operations to convert multiple data inputs to data outputs. Other processing elements (e.g. application of LUTs) can be applied by operations in the calculator script. An XML representation [13] of a B2A0 tag using an iccMAX calculator element can be found in the Appendix.

Figure 3. Order of transforms in an inverse tag of a typical v4 ICC profile

Figure 3 illustrates a typical embodiment of the order of operations in an inverse tag of a v4 ICC profile [5]. The transform step immediately before the 3D color LUT (CLUT) provides a means for modifying the addressing of values in the CLUT with the first curve being applied to L* values, the second curve being applied to a* values, and the third curve being applied to b* values. This architecture just allows for sampling in CIELAB space. This approach cannot be used to convert from CIELAB space to CIELCH space and sampling in CIELCH space.

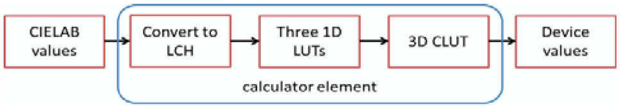

Figure 4. Order of transforms in an inverse multiProcessElementsType tag of an iccMAX profile encoding proposed

Our basic approach is outlined in Figure 4 using an iccMAX calculator element to first transform CIELAB to CIELCH colors. Then 1D LUTs are applied to clip lightness and provide perceptually uniform sampling of chroma and hue. Finally, a 3D CLUT (based on perceptually uniform LCH) is used to obtain device values.

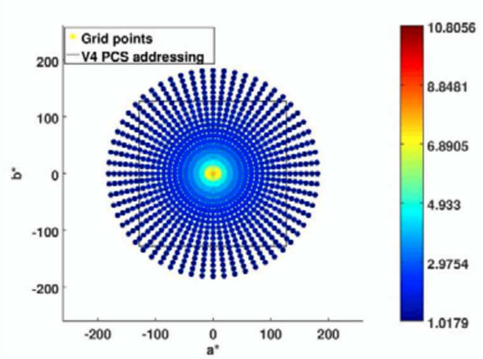

Figure 5. CIEDE2000 color differences between neighboring points of equal-spaced sampling along the chroma direction

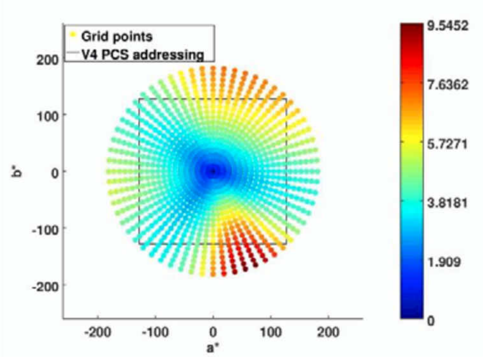

Figure 6. CIEDE2000 color differences between neighboring points of uniform sampling along the hue direction

Proposed method details

The basis of the proposed method is to construct 1D LUTs for chroma and hue such that the CIEDE2000 color differences between the neighboring points in a LCH LUT are closer to being equal.

The CIEDE2000 color differences between neighboring points of equally spaced chroma having identical hue (chroma direction) are shown in Figure 5. The CIEDE2000 color differences between neighboring points of equally spaced hue having identical chroma (hue direction) are shown in Figure 6. As can be clearly seen in these figures, the color difference between equally spaced grid points is not equal along the chroma and hue directions. Since the Euclidean distance between the neighboring points along chroma and hue is equal, the desire is to have the CIEDE2000 color difference between these points also be equal. However, the color difference is larger for points with low chroma and points in the lower part of the figure (representing blue and purple colors).

The chroma scaling algorithm of DIN99d formula [9] was employed to re-sample chroma. The DIN99 color difference formula was developed in 1999 and later adopted as the German standard [10].

$$\begin{cases} e = a^* \cos(50°) + b^* \sin(50°) \\ f = 1.14 * [-a^* \sin(50°) + b^* \cos(50°)] \\ G = \sqrt{e^2 + f^2} \\ C_{99d} = 22.5 * \ln(1 + 0.06G) \end{cases} \tag{1}$$

Figure 7 shows the relationship between C^*_{ab} and C_{99d}, where a* and b* are in the range of -128 to 127. Notice that C^*_{ab} and C_{99d} are nearly linear for values less than 15, and dramatically non-linear when chroma is larger than 15. This explains the results found in Figure 5. By constructing a chroma 1D LUT based on the results in Figure 7 it is believed that more equant CIEDE2000 color differences can be achieved between grid points along the C_{99d} direction.

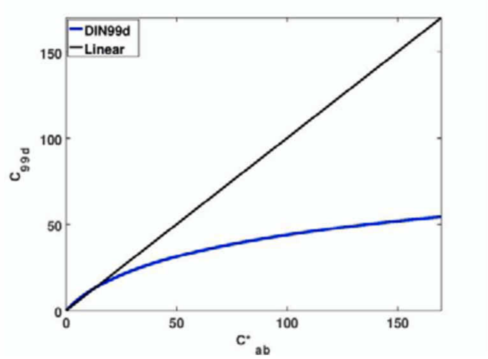

Figure 7. The relationship between C^*_{ab} and C_{99d}

The hue 1D LUT can be constructed by the following computational technique. The hue 1D LUT is denoted by (X_n, Y_n) pairs, where X_n values are the input hue values and Y_n values are the corresponding output hue values and n is the index of the point in the 1D LUT with, X_n having the range of 0° to 360°. First, set X_1 and Y_1 as 0°. Then search for a hue value which has a CIEDE2000 color difference of one unit from the previous value Y_1 and set this value as Y_2. The color difference is calculated by setting the first L*a*b* value as its CIELCH value is (50, C_{max},Y_1) and the second L*a*b* value as its CIELCH value is (50, C_{max},Y_2), where C_{max} is the chroma of 99 (for a*=b*=70), which encompasses typical devices. The value X_2 for this point is X_1 plus a Euclidean distance of one unit. Repeat the search until all the (X_n, Y_n) pairs have been populated. This results in a 1D LUT where the X_n values have a Euclidean distance of one unit in hue direction between neighboring points and the corresponding Y_n values have a CIEDE2000 color difference of one unit in hue direction between neighboring points. Finally, the Y_n values are rescaled to the range of 0° to 360°. Figure 8 shows the hue 1D LUT constructed using this method.

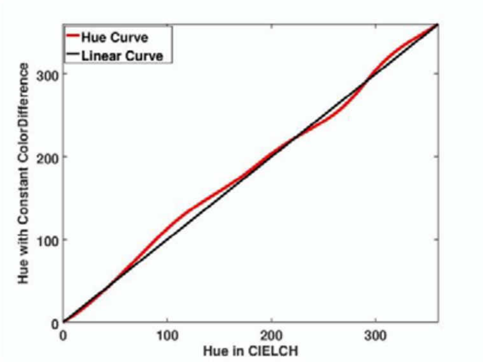

Figure 8. 1D LUT for the hue dimensions created

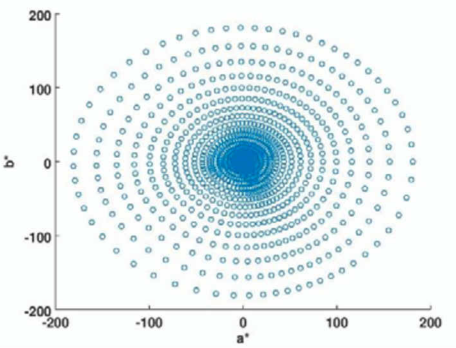

*Figure 9. Proposed sampling method with a granularity of 20*61 along the chroma and hue directions at constant L* of 50*

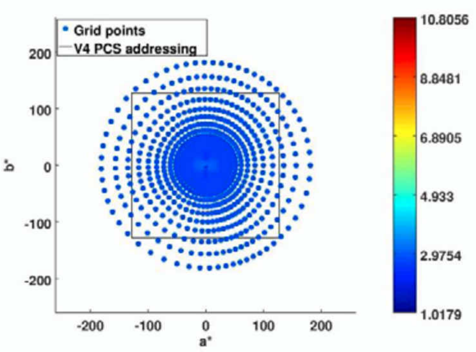

Figure 10. CIEDE2000 color differences between neighboring points of the proposed sampling along the chroma direction

More uniform LCH

In Figure 7, C_{99d} values are compressed at the high chroma colors and expanded at the low chroma colors suggesting that more chroma values should be mapped at low chroma region compared to equal-spaced sampling of C^*_{ab}. In Figure 8, the hue values are compressed at the hue segments of 50° to 220° and 300° to 360°. In contrast, hue values are expanded at the hue segment of 220° to 300°. The optimized LUTs shown in Figure 7 and Figure 8 were used to adjust the positions of the 20*61 grid points along the chroma and hue directions at constant L* of 50 shown in Figure 9. In comparing this figure with Figure 2, we can see that there are more grid points in the lower chroma region than the higher chroma region. In addition, more grid points are distributed between the hue segment of 220° to 300°. Using the sampling method illustrated in Figure 9 readdresses the grid points in CIELCH space to ensure that the color differences between the grid points are more uniform.

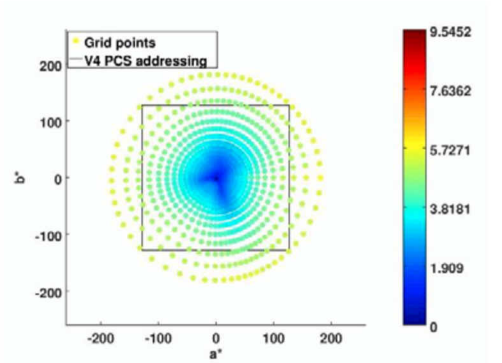

Figure 11. CIEDE2000 color differences between neighboring points of the proposed sampling along the hue direction

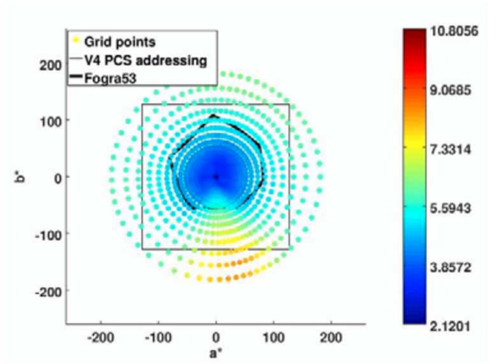

Figure 12. Maximum CIEDE2000 color difference distribution of proposed sampling in CIELCH space with a granularity of 20x61 at constant L of 50*

Figure 10 and Figure 11 illustrate the CIEDE2000 color differences between neighboring points of the proposed sampling method along the chroma and hue directions. Comparing Figure 10 with Figure 5, it can be clearly seen that the proposed chroma sampling approach yields a more uniform color difference than equal-space sampling method in C^*_{ab}, with differences between grid points in the low chroma region being dramatically smaller. It can also be noticed from Figure 11 that the color differences between grid points with constant chroma are generally more equal. However, as chroma increases these differences also gradually increase as a result of the distances increasing.

Figure 12 shows the combined results of applying CIEDE2000 uniformity mapping to both hue and chroma for the proposed method. The maximum CIEDE2000 color difference distribution between grid points and their eight neighbors is shown. When comparing this with Figure 2, it can be clearly seen that the color difference distribution is much more uniform, especially for the low chroma region as well as the hue region between 220° and 300°.

Figure 12 also shows color difference distribution of grid points inside the Fogra53 gamut [12], which is considered as a representative large gamut exchange space covering all printing technologies (offset, gravure, and digital). Comparing to Figure 2, we can see that the color difference distribution of grid points inside the Fogra53 gamut is much more uniform for the proposed method compared to equal-spaced sampling method.

Chroma readjustment

It can be found from Figure 12 that the color difference of grid points increases with larger chroma. To account for this, a chroma readjustment LUT was constructed to produce more uniform color difference distribution, using the similar method to create the hue 1D LUT. The input of the chroma readjustment LUT is C_{99d} values which have a Euclidean distance of one unit between neighboring points and the output is chroma values which produce a CIEDE2000 color difference of one unit.

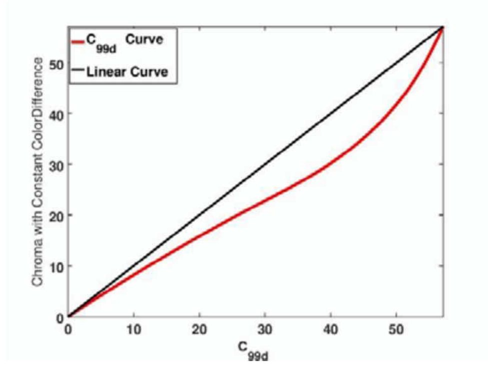

Figure 13. Readjustment of C_{99d}.

Figure 13 shows the constructed chroma readjustment LUT. Figure 14 shows color difference distribution of grid points when chroma readjustment LUT is applied. Comparing to Figure 12, we can see that the color difference distribution of grid points is more uniform when the chroma readjustment LUT is applied. Table 1 illustrates the CIEDE2000 statistics for grid points inside Fogra53 gamut for the equal-spaced sampling method, proposed sampling method with and without chroma readjustment. The mean CIEDE2000 differences go from 6.14 units to 3.62 units and further to 3.01 units, which imply that the color accuracy is improved by 41% and 51%, respectively. In addition, maximum CIEDE2000 differences are reduced to 5.68 units and 4.02 units compared to 10.81 units. This indicates that the proposed sampling method dramatically reduces the overall CIEDE2000 difference range for colors inside Fogra53 gamut compared to LCH equal-spaced sampling approach. Furthermore, the standard deviation of CIEDE2000 differences are reduced to 0.75 units and 0.71 units compared to 2.13 units. Therefore, the proposed sampling method can produce much more uniform color difference distribution than the equal-spaced sampling method.

Implementation of iccMAX profiles

A multiProcessElementsType tag is employed to implement iccMAX profiles which contain the sequence of color transform processing elements depicted in Figure 4. As shown in the Appendix, a multiProcessElementsType contains a single calculator element with a function that utilizes two sub-elements: a curveSetElement and an extendedCLUTElement. The curveSetElement contains three singleSampledCurve structures which store 1D LUTs for lightness, chroma, and hue re-addressing. The lightness adjustment is linear with clipping to the range 0 to 100. The chroma and hue adjustments are as shown in Figure 7, Figure 13, and Figure 8. The extendedCLUTElement stores the relationship between re-addressed LCH and device values. The encoded function in iccMAX calculator element applies stack based operations to achieve the color transform from PCS values to device values using the curveSetElement and 3D CLUT, as shown in Figure 4.

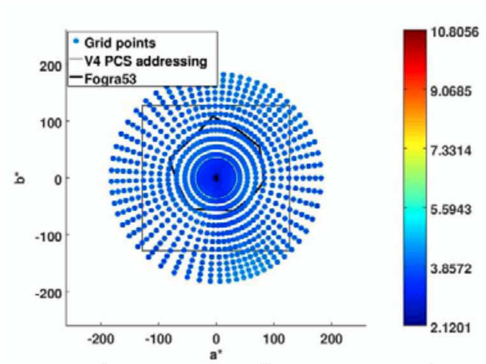

Figure 14 Maximum CIEDE2000 color difference distribution after readjustment of C_{99d}.

Table 1. CIEDE2000 statistics for grid points inside Fogra53 gamut

Sampling method	equal-spaced sampling	Proposed sampling (without Chroma readjustment)	Proposed sampling (with Chroma readjustment)
mean	6.14	3.62	3.01
max	10.81	5.68	4.02
std.	2.13	0.75	0.71
95th-percentile	10.58	4.97	3.95

Results and analysis

In order to evaluate the proposed sampling method, two sets of large gamut CMYK ink jet printer ICC profiles were built for the same printer, ink and media with the same set of measurement data. The first set of profiles, known as "V4 profile" used the CIELAB sampling approach outlined by Rohit et al[5]. The granularities of the V4 profiles were set as 27*27*27 (19683 total), 33*33*33 (35937 total), and 41*41*41 (68921 total) for adjusted (L*a*b*) input channels into the CLUT. The second set of profiles, referred to as "V5 profile" [4], were built using the proposed method. The granularities of the V5 profiles were set as 27*20*36 (19440 total), 33*24*46 (36432 total), and 41*30*56 (68880 total) for the adjusted (L, c h) input channels into the CLUT. These sampling rates were determined to ensure that the sampling along the a* and b* axes were the same as the corresponding sampling using Cartesian sampling. The number of hue samples was then determined to provide tables that have comparable size.

It should be noted that with chroma and hue there is redundancy in grid elements as the zero chroma is repeated for each hue and the zero and 360 degree hue points are duplicated to better facilitate interpolation. Additionally, there is extended coverage outside that covered for a rectangular grid, as shown in Figure 12.

The round trip analysis option of the RefIccMAX wxProfileDump tool was used to analyze round trip accuracy and performance of the profiles. This tool uses the same CMM to apply both v4 and v5 profiles. This analysis involves first getting PCS values for all device values at the sampling rate of the AToBxTag and then performing a round trip of these PCS values by applying the BToAxTag followed by the AToBxTag. This results in PCS values that are inside the output table gamut. A second round trip is performed to determine the round trip accuracy of the profile [15]. Table 2 clearly shows that there is an improvement in the second roundtrip errors for V5 profiles compared to V4 profiles. For similar granularity, there is a decrease in the mean CIEDE2000 errors for V5 profiles. Moreover, the V5 profiles with 27*20*36 and 33*24*46 grid points can reproduce more accurate colors than the V4 profiles with 33*33*33 and 41*41*41grid points. Thus, the proposed method could actually be used to build a V5 profile with reduced number of grid points while exceeding the accuracy of a V4 profile. This would reduce the time required to build the CLUT while also reducing storage cost of CLUT which could be critical in some applications. Furthermore, the number of colors with a CIEDE2000 color difference less than 1 also improves dramatically when using the V5 profiles indicating a significant reduction in interpolation errors for these colors. Since a CIEDE2000 value of larger than 1.0 is considered a noticeable difference to a human observer, an in-gamut image printed through the V5 profiles should look much more accurate than the one with the V4 profiles.

Table 2. CIEDE2000 statistics for second roundtrip

CLUT grid points	27		33		41	
	V4	V5	V4	V5	V4	V5
mean	0.74	0.43	0.52	0.33	0.39	0.26
max	5.09	5.13	4.42	4.71	3.31	3.48
< 1.0	75.2 %	90.9 %	85.7 %	95.3 %	92.6 %	97.6 %

It is believed that some of the difference in accuracy can be attributed to differences in how sampling is performed by the two approaches. With Cartesian sampling (used by V4) the number of "hue" points (or grid points along edge of a box going around the center) increases as the size of the box (or "chroma") gets larger. With polar sampling the number of hue points for each chroma remains constant. Therefore there are more "hue" samples near the neutrals for polar sampling than for Cartesian sampling. Additionally, since the sampling distance from the center remains constant as the hue varies with polar sampling there are more chroma samples being applied to off axis (diagonal) hues.

Performance analysis was conducted in similar fashion to the roundtrip analysis using 60 steps of CMYK (12960000 samples total) while determining the amount of time in seconds to do the round trip analysis. The results can be found in Table 3. On average the V5 processing was 52% slower. The difference in time is attributed to conversion to polar notation and the slight overhead in executing the calculator element main function. Further optimization of calculator processing is warranted.

Table 3. Roundtrip performance comparison in seconds

CLUT Grid Points	27		33		41	
	V4	V5	V4	V5	V4	V5
time	5.53	8.43	5.61	8.51	5.64	8.53

Conclusions

The improvement in perceptual uniformity of sampling in CIELCH space has been demonstrated. This new sampling approach was shown to achieve better perceptual uniformity of sampling between grid points using adjustment to LCH coordinates. The proposed method uses DIN99d formula and CIEDE2000 color difference equation to sample grid points along C* and H* dimensions. V5 iccMAX profiles for a wide gamut ink jet printer were created and analyzed that utilize the proposed uniform LCH adjustments with polar representation for CLUT interpolation. Experiments with these profiles shows that the roundtrip errors are improved for V5 profiles compared to V4 ICC profiles with similar lookup table sizes demonstrating that the interpolation accuracy of the CLUT is improved. This is achieved without increasing the number of grid points in the CLUT. Thus, the proposed method provides a means to maintain or improve accuracy of an inverse CLUT while minimizing the cost of populating and storing such a CLUT. However, performance using the V5 profile was slower than that of a V4 profile showing the need for further optimization of calculator element processing.

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Appendix: Example iccXML

```
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  <MultiProcessElements InputChannels="3" OutputChannels="4">
    <CalculatorElement InputChannels="3" OutputChannels="4">
      <SubElements>
        <CurveSetElement InputChannels="3" OutputChannels="3">
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           StorageType="0" ExtensionType="0">
            0.00000000 1.00000000
          </SingleSampledCurve>
          <SingleSampledCurve FirstEntry="0.00000000" LastEntry="181.01930237"
           StorageType="0" ExtensionType="0" Filename="C-Adjust.txt"/>
          <SingleSampledCurve FirstEntry="0.00000000" LastEntry="360.00000000"
           StorageType="0" ExtensionType="0" Filename="H-Adjust.txt"/>
        </CurveSetElement>
        <ExtCLutElement InputChannels="3" OutputChannels="4" StorageType="2">
          <GridPoints>41 30 56</GridPoints>
          <TableData Filename="LCH-LutDta.txt" Format="text" FileEncoding="int16"/>
        </ExtCLutElement>
      </SubElements>
      <MainFunction>
        { in[0,3] ctop curv(0) clut(1) out[0,4] }
      </MainFunction>
    </CalculatorElement>
  </MultiProcessElements>
</multiProcessElementType> </BToA0Tag>
```

Author Biography

Lin Luo received his Bachelor degree in Biomedical Engineering and Master degree in Computer Science from Southeast University, China, in 2007 and 2010, and his PhD degree in Color Science from The Hong Kong Polytechnic University, in 2015. Currently he is working as a Color Scientist at ONYX Graphics, Inc. His interests lie in the area of color management and digital color imaging, especially researching in Color Management, ICC Building Engine, ICC Apply Engine and Color Measurement.

Max Derhak has worked for Onyx Graphics Inc. since 1990 where he currently functions in the role of Principal Scientist. Max has a Bachelor in Computer Science from the University of Utah, a Masters in Imaging Science at The Rochester Institute of Technology (RIT), and a PhD. in Color Science from RIT. He serves as a Co-Chair of the ICC as well as the Chair of the ICC Architecture Working Group. He is also the initial contributor and maintainer of the iccMAX reference implementation - RefIccMAX.