Perceptual Color Graininess of Printed Pages via flatbed Scanner

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Abstract

Perceptual color graininess is one of the most important visual attributes to evaluate the performance of a printing system. Calibrated flatbed scanner using short-time Fourier Transform (STFT) for color screen removal has been shown to be able to remove the screens in the printed pages for color granularity measurement in the CIEDE2000 color difference space. Perceived color graininess has been found to have correlation with color granularity and luminance in saturated colors. The current paper expands the psychophysical experiment to include printed images with different coverage percentage and various amounts of high frequency spatial noise including printing with more than 4 colorants.

Introduction

Flatbed scanners have been adopted to measure image artifacts such as granularity, mottle, streak and contouring for their capability to efficiently capture large areas of images [1,2,3,4]. However, unlike spectrophotometers, the reported RGB values are device dependent and visually non-uniform with respect to the perceived color differences. Furthermore, for micro-uniformity measurement such as color granularity, the signal can be contaminated by the print halftone screen signals. Methodologies [4,5] have been created to remove the print screen signal before applying any granularity metric that can be represented in the more visually uniform color difference space such as CIEDE2000 [4,5]. In order to address granularity of ordinary color images in addition to uniform color patches, a screen removal method using short-time Fourier transform [6] has been used [5] to obtain color image granularity of scanned images in the CIEDE2000 color difference space. Previous limited psychophysics study [4] using several pure colorants of 60% coverage on uniform patches has indicated perceived graininess's relationship with screen-removed granularity and the patch luminance. The current study expand the study to include samples of the same colorants but different coverage percentage, as well as the effect of additional colorants (such as a 5th color in addition to cyan, magenta, yellow, black and their combinations) on granularity and perceived graininess.

Scanner Calibration

It is well known that most of the color flatbed scanners are not colorimetric device, therefore, the accuracy of the devised color mapping function, M(r,g,b) → (L*a*b*), is constrained to achieve only metameric equivalence. However, it is the high frequency color difference (de-screened noise) within a limited color neighborhood that we are using for color granularity measurement. Previous study [7] indicates flatbed scanners can produce accurate color difference result (therefore can be used for color granularity measurements) in spite of their inherent absolute color mapping inaccuracy. The scanner calibration is performed

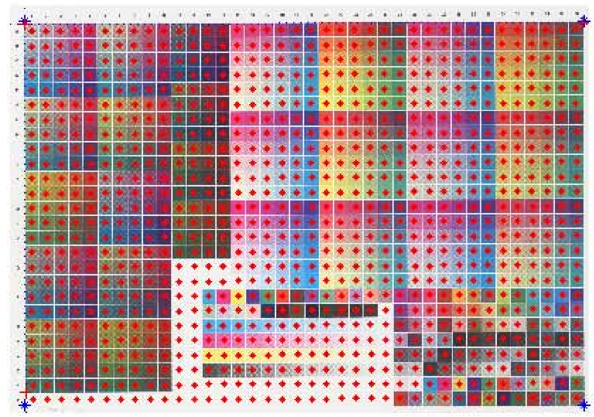

Figure 1: IT8/7.3 (928 patches) test chart

using IT8/7.3 (928 patches) test chart with 4-color printing system (see Figure 1) and using TCMC5 (1218 patches) test chart [8] with 5-color printing system (see Figure 2 for the CMYKR test chart). The printed test charts were scanned by a flatbed scanner at 800 dpi. After the anchor points at the corners have been identified, the centers of the patches are identified given the knowledge of the layout of the test charts. Then a 31x31 block centered at each patch centroid is cropped and the device RGB value is taken as the mean value of these pixels. Similar test charts were measured with a spectrophotometer to obtain the colorimetric data (L*a*b*) of those patches. One can create a mapping function M(r,g,b)→(L*a*b*) by a progressive color-mapping algorithm [4].

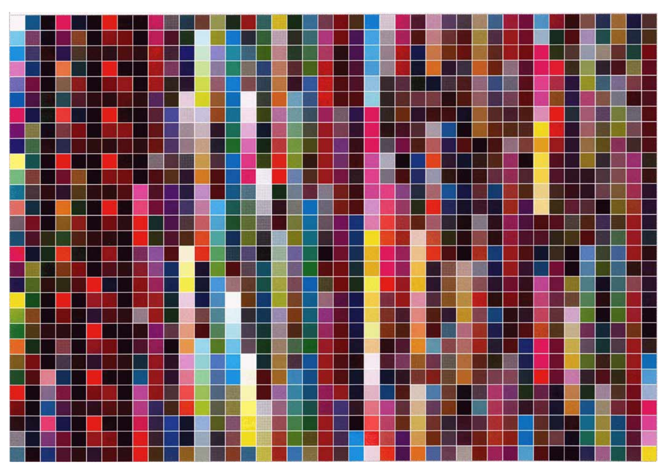

Figure 2: TCMC5 (1218 patches) test chart

Objective Measurement and Psychophysics Experiment

A 45-patch granularity test chart that consists of two portions: (a) 28 patches of various C, M, Y, and K colorant combinations of (30, 50, 70 and 100% dot), (b) 17 patches of simulated popular colors in colorimetric (L*,a*,b*) definition. The granularity test charts were printed in the 4-color mode with two test conditions (1) set CMYK color management off, set CIELab color management intent to absolute colorimetric. This set of prints is going to be used to construct a graininess model in relationship to granularity objective measurements after psychophysics experiment is completed; (2) set both CMYK and CIELab color management intent to absolute colorimetric. Patches on this test set are used for confirmation test of the model. The granularity test charts (3 sets) were also printed in the 5-color mode with red, green or blue colorants in the 5^{th} module in addition to cyan, magenta, yellow and black colorant used in the 4-color mode. Color management intent is set to absolute colorimetric. Patches for this set of 5-color prints are used to confirm the more general usage of the graininess model.

The granularity test charts are scanned by a flatbed scanner at 800 dpi sampling frequency, and short-time Fourier transform (STFT) [5] is used to identify and remove the image screens before granularity metric is applied. In order to optimize for spatial and frequency resolution using STFT, we first estimate an appropriate window size to identify screen frequencies. Then we adopt Fourier transform via overlapping blocks to avoid border effect. If most of the halftone screen signals on images and their harmonics resides in spatial frequency ranges from 50 to 300 line/inch, and a digitized sinusoid with signal length approximately 10 cycles or more will exhibit well-defined peaks after applying FFT. Using a scanning sampling frequency of 800 dpi can provide 100-lpi margin to the highest halftone screen frequency. Furthermore, the block size should be approximately 10x(800/50)=160 pixels. Thus, we select the overlapping block width to be 128 pixels (~4mm) to reach a compromise between the spatial and frequency resolution demand.

Then the screen removal process [5] was applied on the scanned images. Transformation of the scanner RGB value to L*a*b* value is performed using the previously derived color mapping function constructed in the scanner calibration process. The computed L*a*b* values are compared to the colorimetric measured L*a*b* values and found to be within the expected accuracy [4,5,7]. Granularity measurement metric using sampling patch area of $(12.7)^2$ mm^2 and sampling block size of 1.27 mm x1.27 mm (within the patch) as specified in ISO/IEC 13660 is applied on patches of interest. The granularity metric is represented in color variation in the CIEDE2000 color difference space [4,5].

A graininess psychophysics experiment is performed under D50 illuminant on the 28 patches (that covers a range of C, M, Y, and K coverage combinations) from the first set of 4-color prints. The patches are mounted on a gray background-surround of ~0.7 density. Two of the 28 patches are assigned as anchor prints with nominal values of 10 and 80 (higher number for higher graininess). The observers were asked to place the test samples in terms of observed graininess with respect to the anchor prints. Graininess placement beyond the anchor prints is allowed. Fourteen observers participated in the experiment. The highest and lowest graininess numbers for each patch were eliminated to reduce the effect of the outliers. Then the average graininess number is used together with the measured granularity number and the computed L*a*b* values to construct the graininess model. For the confirmation experiment, four patches from the color managed second set of CMYK prints as well from the 5-color sets of prints are used to test the graininess model.

Experimental Results

It has been shown that the presence of black colorant will affect the scanner calibration via various GCR strategies [9]. The same phenomenon also exists when the printing process is extended into five or more colorants. This effect is illustrated in Figure 3. The flatbed scanner is calibrated based on a scanned IT8/7.3 target and a TCMC5 Blue target respectively, and the obtained mapping functions M_{4c} and M_{5c} are adopted to predict the L*a*b* values on both scanned targets. Both mapping functions achieve satisfactory mapping accuracy on the training sets, and results in larger error when used on a test set. The mapping inaccuracy is caused by two reasons: the blue colorant is not present on the IT8/7.3 target and TCMC5 has much coarse sampling points in the CMYK device space than IT8/7.3. As a result, M_{4c} is less accurate when the blue colorant is present on a color patch, and M_{5c} achieves a compromise in overall accuracy when extending prediction capability to larger gamut. Nonetheless, since the color granularity is quantified by microscopic color noise, the color difference in terms of ΔL*, Δa*, and Δb* is more important than mapping accuracy. In Figure 4, we adopt M_{4c} and M_{5c} respectively to measure color granularity on the four test patches where the blue colorant is present, and they show very little difference in the measured color granularity, although M_{5c} results in smaller prediction error.

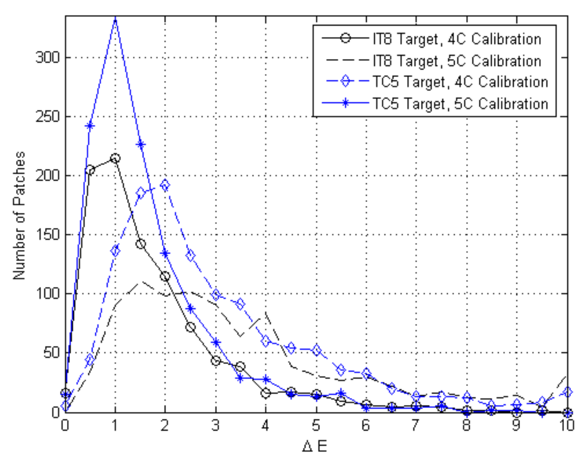

Figure 3: Scanner Calibration accuracy

The yellow and black patches with 50% colorant coverage are selected as two anchor patches based on our previous study where they were identified as the color patches with highest and lowest perceived graininess [4]. No upper limit is imposed on observers to avoid possible nonlinear response compression. Nonetheless, there exist a natural lower limit, 0, representing unperceivable color noise, and this will result in response compression in the lower end as illustrated in the following experiment analysis.

Our original proposed granularity metric algorithm is to adopt the recently updated color difference formula, CIEDE2000, to first quantify the noise present within a selected neighborhood, and quantify the high frequency noised based on ISO/IEC 13660. While it successfully correlated with perceived graininess on single pure color patches, including C, M, Y, K, R, G, and B, when combined with the estimated L* values, we face certain difficulty on patches with two or more colorants. The explanation is that the color difference formula such as CIEDE2000 is developed under 2° viewing subtense; however, the defined graininess is the aperiodic image noise with spatial frequency higher than 0.4 cycle/mm based on ISO/IEC 13660. Assuming the viewing distance is 0.3 meter, and this results in an approximately 2-cycle/degree lower bound in the valid spatial frequency domain relating to the perceived graininess. Namely, CIEDE2000 color difference measurement needs to be modified for high spatial frequency measurement, when more than one colorants present on the test patches (some physically overlap, some does not). The spatial contrast sensitivity functions of human beings for luminance and chromatic contrast indicate that chromatic contrast sensitivities are much lower than the luminance contrast sensitivity [10]. As a result, we can conjure that the perceived color graininess is dominated by the perceived high frequency noise in luminance. Thus, we modify the granularity metric to separately measure high frequency noise in L*, a* and b*. We can expect that the granularity measured in the luminance channel should be the major contributor to the perceived color graininess; moreover, because the chromatic contrast sensitivity function along the Red-Green axis decreases slower than that along the Blue-Yellow axis, we also include the granularity measured in the a* axis as the second factor correlating with the averaged color graininess response.

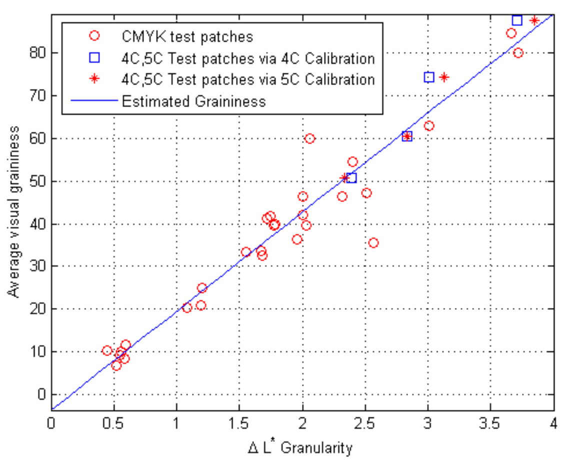

Figure 4: Correlation between the color graininess and the computed granularity in L.*

We first correlate between the averaged color graininess score, VG_c, and the computed granularity in L*, G_L, and the result is illustrated in Figure 4. We can easily explain their relationship via the following single factor model. The negative y-axis intersect can be explained as the result of nonlinear compression at the low end. The samples represented by circles are the primary and secondary color patches, and they are used to derive the linear model in Equation (1). The four test patches printed with multiple colorants including fifth colorants are the test patches to verify the validity of the derived equation. The associated R^2 statistics is 92.15%, which shows that G_L is the major factor contributing to the perceived color graininess.

$$VG_c = 23.16 \times G_L - 3.6$$

Equation (1): Single factor model

We then augment the aforementioned linear model with the contribution from the Red-Green axis, G_a, i.e. a* axis. Figure 5 illustrates the fitted plane via the Dual factor model, and we can see that the second factor, G_a, only slightly affects the regression result, and the R^2 statistics improves to 92.22%.

$$VG_c = 22.83 \times G_L + 0.55 \times G_a - 4.64$$

Equation (2): Dual factor model

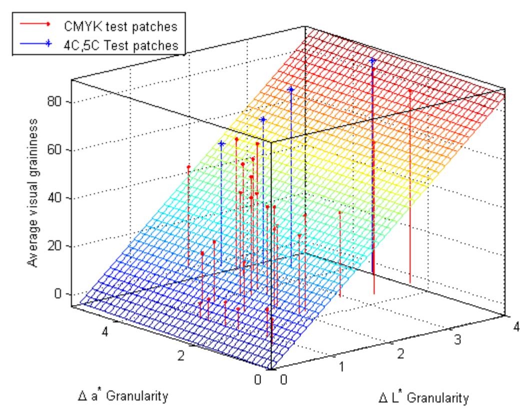

Figure 5: Correlate the color graininess against computed granularity in L and a**

Discussions and Conclusions

A graphical rating psychophysical experiment is conducted to measure the human beings' response on color graininess. 32 color patches are selected where two patches are designated as the anchor samples. The average score of each patch excluding the highest and the lowest score is used to represent the perceived color graininess. Our original color granularity metric is modified to take into account the difference in the sensitivity functions between the luminance and chromatic contrast. Because the graininess is limited to high frequency aperiodic noise, human beings are much more susceptible to luminance granularity than chromatic granularity. As a result, a Single factor model is derived correlating the measured granularity in L* with the averaged color graininess. The insensitivity toward the chromatic granularity is demonstrated in the Dual factor model where the coefficient of G_a is much smaller than that of G_L.

Two patches show a larger deviation from the Single factor model. In one patch that has 100% black coverage with some very small paper spots, the observers' response exhibits bimodal distribution. One possible explanation is that those observers who perceived those white spots penalize the patch by giving a high score while those observers who missed those spots gave a low score. In another magenta patch, the fit to the Single factor model is also problematic. In the future, we plan to extend our experiment to cover more color and screen combinations to further verify our color graininess metric, especially relating to the potential contribution from the Red-Green axis.

References

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