ICC Profile Extension for Device MTF Characterization

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Abstract

We propose a method to maintain image sharpness consistency across different devices, analogous to the way ICC profiles are used to maintain color consistency. The method is based on creating a profile of the perceived blur caused by the printing and viewing process. We show how to measure and analyze the sharpness profile of a printer, and demonstrate that the profile consists of multiple 2D modulation transfer functions (MTF's), varying over different ink combinations and colors. We propose storing the sharpness profile within an ICC profile. The profile can then be used to adaptively pre-compensate for the induced blur, and maintain sharpness consistency.

Introduction

Images viewed on a computer screen are often disappointing when printed, due to changes in color, contrast, and sharpness. In particular, images that look sharp on the screen often look ”soft” and blurry when printed. We propose to address this inconsistency by developing a device (printer) profile of the perceived blur. When printing an image, it may be processed, using the profile, to pre-compensate for this perceived blur. This results in a more consistent sharpness across display devices.

Image enhancement pipelines are generally tuned for a single device, and in many instances do not take into account the print resolution of the image. This means that existing solutions do not provide any mechanism to automatically compensate for the print and viewing blur. This results in artifacts, in low-resolution images which should have very little sharpening, the result is visible ringing artifacts. In high-resolution images which should have strong sharpening, images often appear blurry. Usually pipelines are tuned to provide the best result with the fewest average artifacts, so low-resolution images will have relatively few artifacts, but high resolution images will be blurry.

Some pipelines, such as the HP SmartStream Photo Enhancement Server [4], take image print resolution into account during processing and sharpening, but there is no explicit mechanism for dealing with printer-specific blur. Moreover, as we demonstrate in this paper, it is paramount to take into account the content of the image to be printed. Different colors translate to different combinations of inks and half-toning patterns, affecting the perceived blur. In our method, we construct a set of sharpening kernels, and interpolate between them using the colors of the pixels themselves.

The modulation transfer function (MTF) is a quantity representing the difference between a reference image and a result image (whether printed, scanned or photographed). The MTF is defined as the magnitude of the optical transfer function (OTF) of an imaging system, a measure of the system's resolution. It describes, in essence, the change in contrast in response to patterns of varying spatial frequency [7]. The MTF has long been used to scientifically measure lens performance, and has been used in recent years to measure the performance of scanners and printers. We adopt this approach, and analyze the MTF of a printer, in various conditions, varying over color, ink combinations and modulation angles.

In order to maintain sharpness of a printed image, we construct a set of two-dimensional blur kernels from the set of MTF's. We select for each pixel in the image, the most appropriate blur kernel, and sharpen the image prior to printing.

The ICC specification, ISO 15076-1:2005 for color management, is meant as a standard to translate color data created on one device into another device's native color space. The standard defines a reference color space, unambigously defined (the profile connection space, PCS) which is used for the translation, given a rendering intent. For example, ICC profiles are used to ensure that an image viewed on a computer monitor, maintains color fidelity (as much as possible) when printed. Similarly, we propose to extend this fidelity to sharpness, maintaining the level of detail on different mediums. A natural way to do this, is by introducing additional structures into an ICC profile, characterizing the sharpness profile of a device. The sharpness profile can then be used to pre-compensate for the device blur.

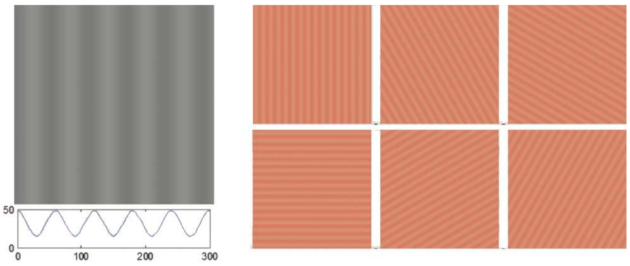
The paper is structured as follows: In the next section we discuss related work. Afterwards we present the test target designed to characterize printer MTF and how to analyze the printed test pages. Following that we discuss embedding the sharpness profile within an ICC profile and how to access it. Finally, in the last section we present our algorithm for adaptive sharpness compensation, applied to an image before printing, and discuss future work.

Related Work

In recent years there have been several papers which have used the MTF to analyze printer performance. In [3] the color modulation of a color Inkjet printer is analyzed using a set of color patches. Each patch contains a sinusoidal modulation signal for fixed frequency, color, modulation direction in the color space, spatial direction of the modulation, and amplitude. A complete set of color patches is used to generate a one-dimensional characterization of MTF for arbitrary modulation, the spatial frequency response for a given set of parameter values. We extend and streamline their method by producing test patches for different ink combinations (not just base inks), and for a large set of spatial directions (as opposed to vertical and horizontal modulations). We refer to this work for further information on MTF and generation of the color patches.

Traditionally, a slanted edge target was used to characterize the MTF of lens and scanners. In this approach, a target with sharp edges is prepared, and acquired by the target device (scanner or camera). The first derivative of the edge profile used to calculate the spatial frequency response (SFR). This approach is taken in [8], modified to work for monochrome printers. The slanted edge target is easy to produce, however it requires constant sharpness and a distortion free image. Therefore, we prefer to use a sinusoidal pattern to characterize the MTF, which is less prone to distortion.

In [1, 2] the quality of printed images is improved by compensating for the MTF, characterized as in [3]. A locally adaptive compensation method is presented. First, the image is decomposed using a bilateral filter, and only the high frequency layer is sharpened. Then, the mean gray level around each pixel is used estimate the bias, which indicates the MTF to deconvolve with. This method can be adapted to work with our more complete characterization of printer MTF. Our proposed compensation method, in contrast, works in the spatial domain. We construct 2D blur kernels, which reflect the anisotropic nature of the printer's blur, and adaptively sharpen the image.



(a) (b)

Figure 1. *(a) We generate a directional color modulated patch for a given color and frequency. (b) We demonstrate that the blur kernel of the printer is anisotropic, therefore we analyze the MTF along several angles.*

Analyzing Printer MTF

We produce a set of color modulation patches to characterize the sharpness profile of a printer. In each patch, a base color is modulated along an axis in the printer native CMYK space, and rendered in a given spatial angle (Figure 1a). Given a base color c in LAB space, and a direction v, the signal is defined as

$$s = c + \alpha(\sin(2\pi f n) - 0.5)v \tag{1}$$

where α is the modulation amplitude. f is the spatial frequency and n is the horizontal coordinate of the patch. Each patch is rotated (in post-processing) by a given angle to produce the final patch.

Our method expands upon the work of Jang and Allebach [3] with two significant additions

1. We find that the underlying blur kernel of the printer is anisotropic, and measure the MTF for a set of angles $\{0, 30, 60, 90, 120, 150\}$ (Figure 1b). In [3] only horizontal and vertical spatial directions are analyzed.
2. We find that the perceived blur is dependent on the combination of inks printed. Therefore we set out to measure the MTF for a large sampling of colors (varying over luminance and color channels). We produce patches for fixed points $32, 64, 96, 128, 160, 192, 224$ (assuming 8-bit values) around the major and minor printer color axes: Cyan, Magenta, Yellow, Black, Red, Blue and Green.

Designing the Test Page

In order to prepare a set of test pages to analyze the sharpness profile of a printer, we must know in advance the model of the printer, its print resolution, and preferably its ICC color profile. It is beneficial to also know the page size of the scanner to be used, and its maximal scanning resolution. Knowing this we can determine the set of frequencies and color channels to test, and produce a set of test pages.

The color modulated test patches we generate vary by color (color channel and luminance), frequency and angle, and number in the hundreds. In order to streamline the printing, scanning and MTF analysis process, we group the patches together. First, the patches are organized in test grids, where the frequency and color channel are fixed, and the variance is over angle and base luminance. We then arrange the test grids on pages, where grids with similar frequency are grouped together. This is done to simplify the packing of grids on pages and the scanning process (higher frequencies require smaller patches, but also a higher scanning resolution).

```xml
<?xml version="1.0" encoding="utf-8"?>
<page Angles="[0 30 60 90 120 150]"
Bias="[32 64 96 128 160 192 224]"
 grid_size="[3 3]"
image_size="[2.155 2.45166667]"
 num="19" patch_size="[0.265 0.265]">
   <image Color="C" Freq="60"/>
   ...
   <image Color="M" Freq="100"/>
</page>
```

Figure 2. *A sample QR code describing a test page, and the embedded XML description.*

A set of markers are added to each grid, as described in [3], to aid the analysis stage. Additionally, we add to each page a QR code [6]. A QR code is a two-dimensional barcode, which can encode a large amount of information. We encode for each page the set of test grids embedded in it, and the structure and size of each grid (patch size, frequency, color channel etc, Figure 2). This further helps streamline the process, as the scanned test pages no longer need to be in a specific order, nor divided to individual test grids.

Finally, each test page is saved as a TIFF image file, in CMYK colorspace, and the appropriate printer ICC profile is embedded within the file (Figure 3). We print the test pages in the designated printer, and proceed to scan and analyze them.

Scanning and Analyzing the MTF

Once we have a set of printed test pages, we use a flatbed scanner to scan them, in our case we used an Epson GT10000 scanner, scanning the pages at 1200 DPI. We take into account the color calibration and the scanner MTF similarly to [3].

For each scanned page, we automatically locate and decode the QR code (Figure 2). The QR code contains the number of test grids on the page, and the composition of each one (color, angle and frequency values). We then use the secondary markers (cross

Figure 3. *Patches are set in test grids varying over angle and luminance, and then on pages grouped by frequency.*

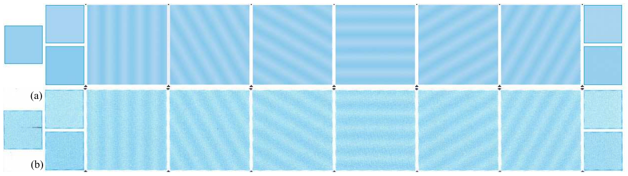


Figure 4. *Top row: generated color modulated patches. On the left and right reference patches with the two modulated color values. Bottom row: same patches, after scan.*

symbols) to extract each test grid, and extract the individual color modulating patches within each grid.

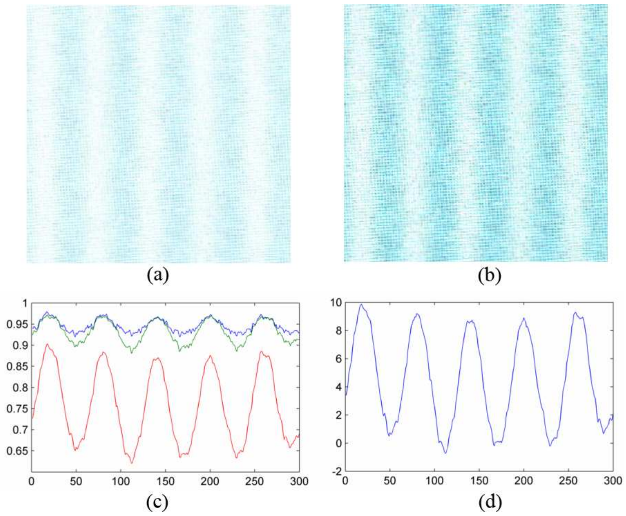
For each scanned patch we know its base color, amplitude, angle and frequency. Therefoer, we can calculate the discrete Fourier transform, and determine the frequency response for that patch. We start by sampling the color of the reference patches to the left of each line in the test grid. These patches are the high and low peaks of the modulated color signal (Figure 4 a and b respectively). We convert the scanned RGB values to LAB, adjusting for the scanner RGB linearization. This defines two colors a and b in LAB space between which the color modulates.

Given a scanned patch (Figure 5a) we perform the following steps in order to extract its frequency response:

1. Linearize the pixel RGB values of the current patch (F.5b).
2. For patches with an angle different than 0, we rotate the patch such that the modulated signal is horizontal.
3. Calculate the mean color for each column, so we have an average signal sampling (F.5c).
4. Convert the values to LAB, and project them to the vector defined by $a-b$ (F.5d).
5. Measure the distance between each project point and a, a distance measured in δE.
6. Calculate the DFT for this value, the magnitude of which reveals the peak-to-peak value of the modulated signal.
7. The frequency response $F_{AB}(f)$ for this patch is defined as the DFT magnitude at the corresponding frequency.

Finally, the MTF $M_{AB}(f)$ in LAB space is defined as the ratio of the frequency response F_{AB} to the color difference ε_{AB}. Thus, for each color channel sampled we retrieve $N_f \dot{N}_a$ MTF values, where N_f is the number of frequencies sampled, and N_a the number of angles sampled. As can be seen in figure 6, the MTF varies considerably for different colors channels (ink combinations). Also demonstrated, the variance in the MTF over different spatial modulation angles, and bias levels.

The FR and MTF values are stored in the ICC color profile as described in the next section.



(a) (b)

(c) (d)

Figure 5. *Given a scanned color modulated patch (a), we compensate for scanner linearization (b). We project the pixels spatially to create a 1D signal (c) and convert that signal to LAB color space. We then project the points in LAB space, to a line stretched between the two modulated LAB values (d).*

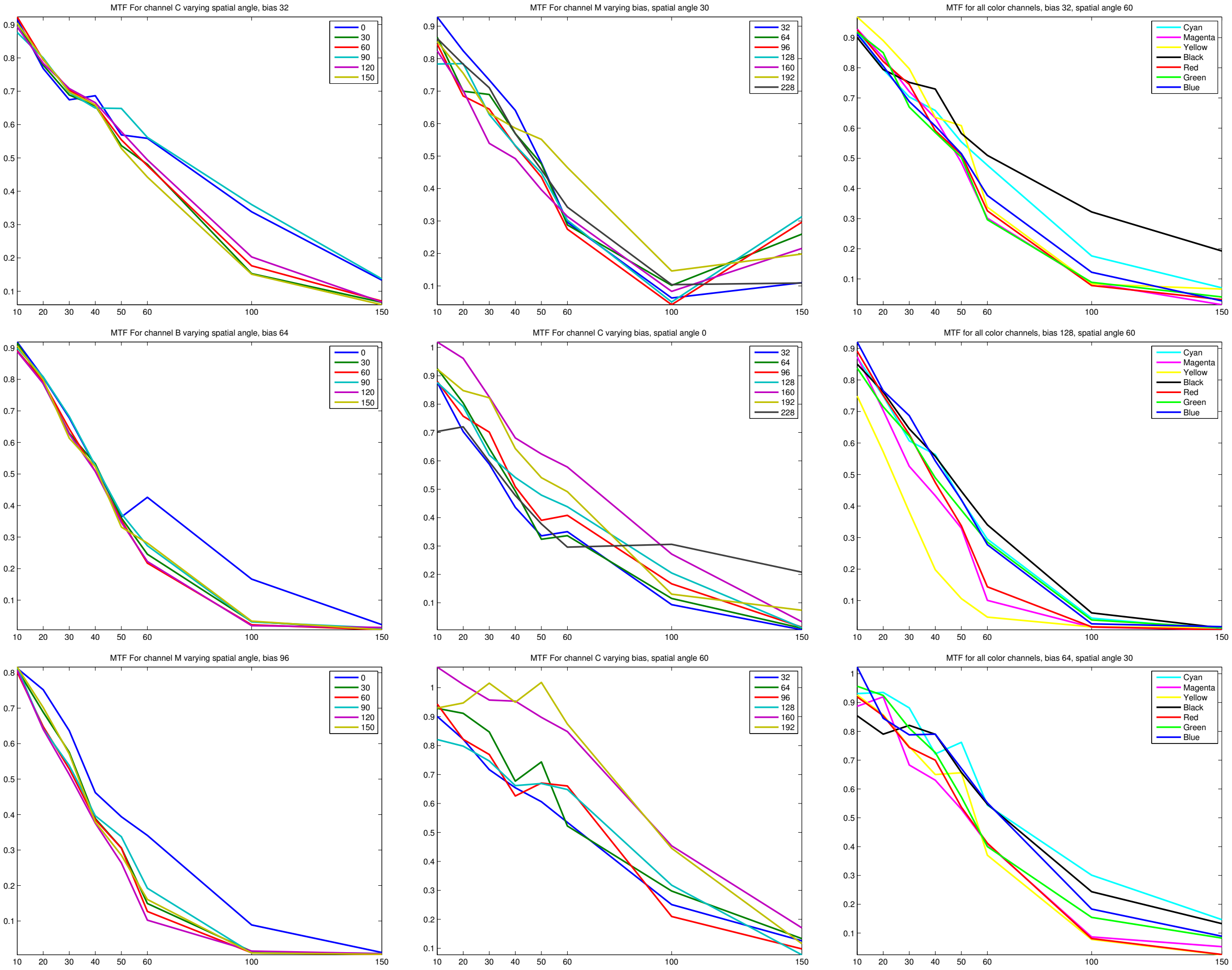
Extending ICC profiles

Storing device sharpness characterization within an ICC profile will allow imaging pipelines access, via standartized API's to the information. Different algorithms may then be implemented, using the sharpness profile, to compensate and improve image fidelity. We propose to store the data in the ICC profile as optional data in a relatively raw form. The sharpness profile will be stored as an array of 2D MTF's. Each one is defined by an array of 1D MTF's, each of which corresponds to a different spatial angle and consists of an array of scalar values. The scalar values are the measured frequency response for a set of pre-defined frequencies. The 2D MTF's are indexed by LAB color (the sampled color channels and bias in each channel). The suggested structures (in C notation) are

```
typedef struct {
cmsCIELab color;
cmsFloat32Number** data;
} cmsMTF;

typedef struct {
cmsUInt32Number ncolors;
cmsUInt32Number ndegs;
cmsUInt32Number nfreq;
cmsFloat32Number* degs;
cmsFloat32Number* freq;
cmsMTF* mtfs;
} cmsSpatialProf;
```

cmsMTF is a 2D MTF, and has the color for which the response was measured, and a two-dimensional array of data points



(a) (b) (c)

Figure 6. *The printer MTF shows significant variance over the different parameters in all three characterized printers, an HP Indigo 5000 (top row), HP Designjet 130 (middle row) and HP Laserjet (bottom row). The variance is evident for varying spatial angles (a), varying bias levels (b) and varying color channels (c).*

in polar coordinates, the first of which is angle and the second of which is frequency. The number of data values in a 2D MTF is defined by $ndegs$ and $nfreq$ in the $cmsSpatialProf$ structure. $cmsSpatialProf$ defines the entire device characterization. It specifies how many 2D MTFs there are, and the frequencies at which the response was measured ($nfreq$ and then the array of frequency values in $freq$), and the angles for which the frequency response was measured ($ndegs$ and then the array of angle values in $degs$).

Storing the sharpness profile within the ICC color profile, is the first step to enable image sharpness compensation. However, such an algorithms requires additional information, not present in the profile. In the default usage of color profiles, only the color values of a pixel in profile connection space (PCS) are needed to convert it to device space using the profile. Sharpening a pixel requires knowledge of its surrounding neighborhood, as well as image and print resolution.

Therefore, when processing an image, we cannot view a pixel as a single point. We must be able to place it in context of its neighbors, and the whole image, in order to apply any algorithm. Currently, as discussed in the following section we implement this functionality as a plugin in LittleCMS [5].

Results and discussion

Given an output device sharpness profile, stored within an ICC profile, we extract it and convert it to a full 2D sharpening kernel. In order to construct the kernel, we need to fix the image and print resolution. Our algorithm, for a given color channel and bias is defined:

1. Extracted *nAngles* MTF's from ICC profile, where *nAngles* is the number of different angles sampled.
2. Each MTF is sampled at a set of fixed frequences (10,20,30,40,50,60,100,150 cycles per inch). Fit a spline to each MTF, sampled at the points $[1,150]$.
3. Interpolate the MTF value to all angles in the range $[1,360]$ degrees.
4. Take the inverse 2D FFT, normalize so sum of elements is one.
5. Create a sharpening mask by subtracting two from the origin.

Examples for the resulting kernels can be seen in Figure 7. Each kernel is associated with a base LAB color. For each pixel in an image we process, we select the nearest kernel. We then smooth the kernel selection map, and apply the kernels to the image. An example of an image sharpened for print on an HP Designjet 130 can be seen in Figure 8.

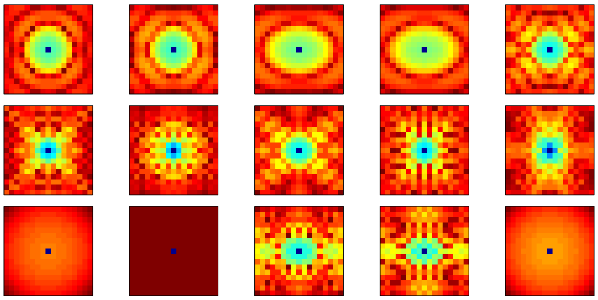


Figure 7. *Given a printer sharpness profile, we construct a sharpening kernel using the MTF's for a given color channel and bias. Visualized are five sample kernels for each test printer. The visualization is done using a* $-log(k)$ *function on the kernel. The top row is an HP Designjet 110, The middle row is an HP Indigo 5000 and the bottom row is an HP Laserjet office printer.*

(a)

(b)

Figure 8. *Given an image (left) and a printer sharpness profile, we adaptively pre-sharpen the image (seen on the right), such that when printed it will appear with consistent sharpness.*

References

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Author Biography

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Ron Banner is a researcher for HP Labs Israel since September 2006. His research interests are in image restoration and the theory of art. Ron published fifteen papers in highly selective journals and conferences and has four US-filed patent applications. His first paper, which appeared in the premier conference of the computer networking field, earned him the Best Paper Award for 2004. One of Ron's recent achievements in the lab was the development of a suit of optimizers to apply the lean manufacturing philosophy to print production environments.