Color Gamut Mapping Using Spatial Comparisons

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ABSTRACT

This paper describes a simple research and pedagogical tool for thinking about color gamut compromises. The idea is to fabricate Mondrian-like images that have patches of different colors with intermediate spatial complexity between single stimuli and real complex images. These Gamut Mondrians can be used to illustrate the observations found in the literature and to act as a simple experimental system to explore the principles of Gamut Mapping Algorithms.

Keywords: gamut mapping, Mondrians, retinex

1. INTRODUCTION

Attempts to make printer output look like computer displays have no ideal solution. The physical differences between dyes and emitters and transparent filters create systems with very different gamuts. Their color spaces overlap is about 50% of combined volumes. Research on Gamut Mapping Algorithms (GMA) is the search for the best compromise. Since the pioneering work of Maureen Stone and colleagues there have been many approaches to find the best compromise.

Gamut mapping is an ideal problem for computer image processing. Two parts of the problem are well suited for computer analysis. First, efficent processes are needed to transform the millions of pixels in an input image to the desired output. Second, finding the best compromise in a complex three dimensional color space is best done by computer analysis that can evaluate all possible combinations and identify the compromise with minimal error. In gamut mapping the optimal compromise is the GMA chosen by observers. The gamut mapping problem becomes more interesting when we realize that we do not know the how to define the error we want the computer anysis to minimize.

Morovic and Luo[1] have reviewed the extensive literature and described three generations of Gamut Mapping Algorithms (GMA). Early investigations studied the geometric projections from the out-of-gamut pixels to the optimal in gamut values. These approaches used efficient 3D mathematical transforms that could nearly instantaneously transform colors in display space to colors in printer space. All that was needed was the rules of how the eye made these transformations. The geometrical transform ideas are widely used today. However, they are not considered the optimal compromise. Some of their strengths and weaknesses will be discussed below.

Computer displays and printers are not the only example of gamut mapping. In fact the problem has been with us for 60 years in the Graphic Arts, since the advent of color transparency photographs used to make color halftone or gravure prints. Despite the large mismatch in color gamuts, the color transparency has been the universally preferred image source for commercial color printing. Tony Johnson, an expert in color graphic arts proposed a different approach to gamut mapping. Before applying geometrical transforms, he accumulated a set of data from expert printers about their empirically defined procedures. The algorithm, called CARISMA, fits transforms to what printers do. It is much more practical than theoretical, and generates a much less elegant and less efficient geometrical transform, but it works well. CARISMA applies different methods of empirical correction for each hue depending on the shapes of the two gamuts.[1]

Jan Morovic chairs the CIE Technical Committee 8–03[2] on Guidelines for the Evaluation of Gamut Mapping Algorithms which is working to establish comparison techniques by unbiased observers. Such an evaluation is equivalent to the work required for a Ph.D. thesis. These studies are extremely important and must be done to finally resolve the optimal GMA compromise. This paper, however, describes a simple research and pedagogical tool for thinking about color gamut compromises. The idea is to use patches of different colors to fabricate Mondrian-like images[3] that are intermediate between single stimuli and real complex images. These Gamut Mondrians can be used to illustrate the observations found in the literature and to act as a kind of bench-top experimental system to explore the principles of GMA without multi-year research efforts. If one believes that the problem of finding the best GMA compromise is that we have not yet defined the "error" our computers will minimize, then these simple gamut Mondrians will help us to think about the metric for the optimal compromise.

Unfortunately, many of these simple displays vary in color and are constant in luminance. In such images there is no structure in a black and white reproduction. This paper will describe in principle a number of different color displays shown in the presentation. They will not be illustrated in this proceedings. It is far too confusing to refer to figures and then try to explain what you would see, if you were not looking at a different display.

2. GAMUT MONDRIAN DISPLAYS

The displays used are meant to first illustrate well known principles of gamut mapping and to help develop new systematic understanding of why humans are so insensitive to some transformations and so sensitive to others. The reason that there are so many different approaches is that none have been established as the best, or even the "good enough". The following discussion will include examples of primitive out-of-gamut to gamut transformations and their artifacts. It will describe well known "soft clip" techniques and zone techniques. The final displays will include spatial image transforms that attempt to provide a theoretical framework consistent with the empirical approaches already described.

2.1 Out-of Gamut to Gamut Transforms

These display targets work with two hypothetical gamuts, one large and the other small. Usually the targets are made using a printer or a display. The selection of only one medium for comparison experiments makes the task of calibration much simpler. Only one measuring device is required and only internal consistency is required. In the following discussion we will describe all experiments as prints, but display and combinations of display and prints can work as well.

First, we make a pair of prints using the large and small gamut calibrations. The simulation of the large gamut system is the printer response to a calibration target that covers the entire range of input digits in R, G, B and their combinations. The small gamut is created by measuring the colorimetric values (X,Y,Z or L*a*b*) of the large gamut print and applying a significant gamut reduction. The second print will use only a fraction of the large gamut's colorimetric range.

Having created the calibrated simulation of two different gamuts on a single printer we can create two Gamut Mondrians using large and small gamuts. The large gamut Mondrian contains a series of pairs of adjacent rectangular patches with different hues and different lightnesses. In each case, the upper member of the pair is on the gamut of the small gamut space. The lower member of the pair is on the gamut of the larger gamut space close to the colorimetric values of the upper member. It is easy to visualize the results of a primitive GMA that maps the out-of-gamut colorimetric value to the nearest gamut point. In the large gamut print the upper member of each pair will appear similar, but different from the lower rectangle. In the small gamut print the top and bottom will be identical. They have to be because the top was selected to be at the small gamut limit and the bottom was moved by the GMA to be on the small gamut. Visually we have replaced all the pairs of rectangles with squares. The above small gamut print illustrates the problem that graphic arts printers have learned to avoid. Namely, preserve the detail information of the values that fall between the large and small gamuts.

2.2 Soft Clip and Zone Transforms

From the very beginning, the above illustrated "Out-of-Gamut to Gamut" transforms were avoided because of their severe artifacts. Techniques were developed to have a smooth transition that slowed the problem of loss of discrimination between the top and bottom members of the pairs. These techniques are reminiscent the techniques in photography used to represent a dynamic range of 1000:1 from a real world scene on a 30: 1 print. Low-slope changes provide discrimination, even though it is an inaccurate reproduction.

MacDonald et. al.[4] described their recent addition to GMA models. Here they described three zones. The first is the region between small gamut and large gamut. The third is the region in color space close to the gray axis (vertical axis in L*a*b* space) that is unchanged by the GMA. The second is the region between the two that is shaped by the GMA. MacDonald et al have described a new method that introduces a different point of convergence for different lightnesses.

There are a great many different ways to apply soft clip techniques in this GMA zone. It is far beyond the scope of this paper to attempt to discuss them. Two observations are very clear. First, the soft clip techniques are far superior to the “Out-of-Gamut to Gamut” Transforms illustrated above. Second, they all increase the magnitude of the colorimetric error between the large and small images. The reason for this is very simple. In the “Out-of Gamut to Gamut” Transforms, all in-gamut colors are reproduced by identical values - zero error. The sum of the absolute colorimetric errors is the sum of the individual projections from out-of-gamut value to the nearest gamut value. All GMAs that improve performance, do it by increasing colorimetric error. The better performance has been achieved by replacing zero-error values for in-gamut pixels with larger errors. Other Gamut Mondrians illustrate this point.

2.2 Observation Based Transforms

As already described, CARISMA is the assembly of graphic arts experience. It is a complex transform that first analyzes the magnitude of compression required and the treats each hue independently. Kang et. al.[5] recently described experimental matches to find the observers’ choice of best compromise for each color independently. Their data lead to a model with three ranges. In the upper level (high lightnesses) there is a high point of convergence, in the middle level (middle lightnesses) there is no point of convergence, in the lower level (low lightnesses) there is a lower point of convergence.

The common denominator between CARISMA, Kang’s observer data and complex zone GMA, such as MacDonald’s, is that there is no single projection to a single convergence point in color space. The “Out-of-Gamut to Gamut” transforms got their speed and efficiency from the fact that there was only one rule. (Project all the out-of-gamut points to a common point, such as L*=50, a*=0, B*=0). As already mentioned, observers prefer multiple end points and complex transforms. The more complex the transform, the greater the colorimetric error between the large-gamut original and the optimal small-gamut reproduction.

2.3 Spatial Transforms

At some point in the future we need to return to the theoretical basis of what we are doing. There is a flaw in an argument that we base our calculations on colorimetry, and that we find our best results are consistent with larger than minimal colorimetric error. Defending our position with the argument that larger than minimal colorimetric errors are necessary, but not sufficient for good color reproduction does not help. Wouldn’t it be better to look for a meaningful metric of color reproduction. Such a metric must give minimal errors for the best reproduction

McCann[6] has suggested a metric using spatial comparisons to explain the quality of reproduction. In it the absolute value of the patch is less important than its relative value in each separation. Although it is an unsophisticated metric, it works much better than non-spatial colorimetry.

The simplest interpretation of spatial computations is that it will make use of the human visual process described as color constancy. Here we observe that large uniform changes in illumination cause small changes in images. We also observe that small local changes in light cause large changes in appearance. If we could harness this effect in our solution to gamut mapping we could get much better reproduction. An illustration of this effect is found in a set of nine “umbrella “ displays.[7] Ten identical isosceles triangles radiate from a common apex so as to form a decagon. Each triangle in the display has a different Munsell value. (The specifications for all areas are in Munsell notation. This avoids the problems introduced by the inconsistencies found in L*a*b* spacing.[8-12] The “Original” has 10 triangular areas. The top triangle has the same L*a*b* values as Munsell paper 5R 7/6. The remaining 9 areas are all 7/6, each of them are 4 Munsell pages apart [5YR, 5Y, 5GY, 5G, 5BG, 5B, 5PB, 5P, 5RP]. Thus we have placed the 10 triangle in a circular array of constant lightness and chroma in color space.

All 10 colors in all the remaining 8 targets differ from the original by only one chip in the Munsell Book. The “lightness” series varies in lightness. Each corresponding area in the lighter display is 8/, and is 6/ in the darker. This change in stimulus is a global shift. It produces noticeable, but acceptable changes in appearance. The changes for all 10 areas are about the same magnitude.

The “chroma” series varies in color saturation. Here all 10 papers have /4 in the less colorful and /8 in the more colorful display. The chances are noticeable, but regarded as acceptable reproductions.

The “hue” series varies in the page of the Munsell book. Here 5R is replaced with 2.5R in redder and 7.5R in more purple. The same shift was applied to all 10 areas. The chroma /6 was chosen so that one hue page in the Munsell book equals one chip in lightness value and one chip in chroma. Here the change in color appearance is small, but noticeable and acceptable as good reproductions.

So far, all the changes have been global shifts. All 10 papers have moved in the same direction in color space. Such uniform movement is reminiscent of the changes found in color constancy experiments in which the paper display is constant, while the intensity and color of the illumination changes. In color constancy experiments we are familiar with this kind of result, namely that colors change very little with large global shifts in illumination. As well, it is common practice in photographic systems to find small apparent changes with large global density shifts, while local changes of the same magnitude are clearly visible.

The final "random" series shows the effect of pseudorandom color shifts. As above, each color patch is one Munsell chip different from the Original. Nevertheless, independent changes produce both large and small visual changes in appearance. These local area changes make poor reproductions. They distort the appearance of the original in a way that makes them unacceptable reproductions. This is exactly what we do when we change an out-of-gamut pixel and leave an adjacent in-gamut pixel unchanged.

As suggested by Mike McGuire the analogy to color constancy is very compelling. Changing the colors independent of the neighbors disrupts the spatial ratios. Changing the local ratios in the context of a color constancy experiment is the same as changing the reflectances of the areas. Changing reflectances of individual papers (local shifts) cause big changes in appearances, while changes in illumination (global shifts) cause small changes.

The suggestion from these experiments is that color gamut calculations using spatial comparisons can lead to better in-gamut reproductions. Colorimetrically they will have larger color difference errors, but they should look better. The same color constancy mechanism, that reduces large physical shifts in illumination to small appearance changes, can be employed to make gamut-limited reproductions look better.

McCann has proposed a new gamut technique based of the spatial image comparisons used in Retinex calculations.[13-15] The calculation begins by making two images of the scene. One is the large gamut goal; the other is the small gamut representation called the "Best". The "Best" image can be made by any number of GMAs to project out-of-gamut points to the gamut. The GMA and the color space of the "Best" is not important. The spatial comparisons step takes the ratios of radiances in the "Goal" record and multiplies it by the old product in the "Best". This product is reset to the "Best". The color space of the "Goal" is very important. It characterizes the visual boundaries in the image that must be preserved. The calculation creates a new image that has the same ratios (when possible) as the "Goal". The output of this process looks more like the Goal than the Best, and has very large colorimetric errors.

The reset to "Best" restrains the color space to the vicinity of the small gamut device. The exact shape of the low gamut is not important. The important property is that the reset minimizes artifacts, just as we have seen in soft clip transforms above. The Retinex soft-clip is image-based and depends on the content of each image.

The calculated output is a set of colors that look more like the "Goal" than the "Best" even though the are with the smaller gamut of the "Best". As with observer based transforms the projections from out-of -gamut colors to in-gamut colors do not have a common point of convergence.[14] Other Gamut Mondrians illustrate the results of spatial comparisons and spatial metrics for image reproduction.

DISCUSSION

Colorimetry, in its present form, restricts input to a single pixel. In such a format it cannot calculate the best compromise for gamut mapping algorithms (GMA). Geometric projections that create minimal error have the lowest colorimetric error. They have severe artifacts that make reproductions unacceptable. The introduction of "soft clip" transforms used in photography removes artifacts, but increases colorimetric error. When observers are asked to find the best color compromises they report complex GMAs with many convergence points. These GMAs do not operate by minimizing color error. Spatial GMAs show considerable promise. They provide a means of automatic calculation of the best compromise by minimizing spatial contrast errors. Although in principle, comparing each pixel in the image with all the other pixels is more complex than one pixel transformations, very powerful and efficient algorithms for spatial comparisons are available.[16,13,17]

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