Multispectral Gamut Mapping and Visualization – a First Attempt

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ABSTRACT

A method is proposed for performing spectral gamut mapping, whereby spectral images can be altered to fit within an approximation of the spectral gamut of an output device. Principal component analysis (PCA) is performed on the spectral data, in order to reduce the dimensionality of the space in which the method is applied. The convex hull of the spectral device measurements in this space is computed, and the intersection between the gamut surface and a line from the center of the gamut towards the position of a given spectral reflectance curve is found. By moving the spectra that are outside the spectral gamut towards the center until the gamut is encountered, a spectral gamut mapping algorithm is defined. The spectral gamut is visualized by approximating the intersection of the gamut and a 2-dimensional plane. The resulting outline is shown along with the center of the gamut and the position of a spectral reflectance curve. The spectral gamut mapping algorithm is applied to spectral data from the Macbeth Color Checker and test images, and initial results show that the amount of clipping increases with the number of dimensions used.

Keywords: gamut mapping, spectral image reproduction, principal component analysis, gamut visualization, spectral gamut

1. INTRODUCTION

Multispectral color imaging has become an important field of research during the later years. For some time, spectral acquisition systems have been available (see e.g.,[1–4]). Recently, devices for multispectral color printing have also been developed and characterized.[5–7] However, when multispectral images from the acquisition systems are to be reproduced on such printing devices, the problem of gamut mapping arises. The gamut mapping problem is now thoroughly studied in the case of color image reproduction, but not in the case of multispectral, and hence multidimensional, reproduction. It is not even clear what the concept of a spectral gamut would mean.[8]

Previously, the authors developed a software tool – ICC3D – for visualization and mapping of color gamuts.[9] This program has proved a powerful tool for research on color gamut mapping and related topics. In the present work, we extend the ideas behind this software to also deal with the analogue multidimensional problems. The software is now able to read multispectral image files in several formats, as well as spectrophotometric measurement files used for calibrating printing devices. From these data, spectral gamuts for both devices and images are defined as convex hulls of the corresponding data. This can be done in a space with reduced dimensionality using principal component analysis. These gamuts can in turn be visualized as intersections with 2-dimensional planes.

One particularly interesting mode of visualization is when one spectrum from an image is visualized along with the device gamut in the 2-dimensional plane defined by the given spectrum, black, and the spectrum of a neutral color within the reproduction gamut. Then one can observe directly whether or not the given spectrum is within the gamut, and, if not, how much it must be changed in order to come inside the gamut.

This observation has led to a novel attempt at a spectral gamut mapping algorithm: The in-gamut spectra are left unchanged, whereas the out-of-gamut spectra are mapped to a spectrum on the gamut boundary within this plane. The resulting spectral gamut mapped images can be visualized under different illuminants along with the original image for on-screen comparison.

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2. BACKGROUND

The previously published work on the subject of color spectra all agree that spectral reflectances tend to be more or less smooth, with recurring patterns that make it possible to represent a reflectance curve by a smaller number of components.[10–12] The actual number of components necessary to represent an arbitrary reflectance with sufficient precision, is yet to be determined, although application specific suggestions of 3 to 21 dimensions exist.[12] Principal component analysis (PCA)[13] is a method that is commonly applied to reduce or discover the dimensionality of data sets, and its application on spectral data is well known.[12, 14] PCA can be implemented by calculating the covariance matrix of the data, and performing singular value decomposition (SVD) on this matrix. The method is applied to data where the variables are correlated, and transforms the data into a set of uncorrelated variables ordered by the variability of the variables. The result is a linear transformation, where the vector space basis of the data is changed in such a way that most of the information about the data samples is found in the first components, while the remaining components contain less information. By selecting a number of the first (principal) components to represent the data, enough information can be maintained to reconstruct the data without introducing a large error.

When working with reproduction of images and colors, a critical aspect of the process is the application of gamut mapping. This is necessary in order to transform the source to the color space of the output device. Its goal is to make the reproduction as close to the original as possible, given the limitations imposed by the capabilities of the output device with regards to the set of available colors. This has been a particular area of interest in color imaging research for some time, and a variety of possible image dependent and independent algorithms have been developed. Morovic and Luo[15] have conducted a survey of the available gamut mapping algorithms (GMAs) for conventional color reproduction, but there has been no attempt at extending these principles to the area of spectral color imaging.

The application of GMAs depend on the availability of a suitable gamut boundary descriptor (GBD), since the extents of the gamut need to be found. Convex hull has previously been suggested as a possible method for computing a GBD for spectral data from reproduction media.[8] The convex hull of a set of points consists of surface elements called facets. Each facet has the same number of vertices as the dimension of the space in which it was calculated, and defines a hyperplane. If a point is on the same side of all the hyperplanes of all the facets, it is considered to be a part of the convex hull. This provides an easy method for deciding whether a reflectance is within the spectral gamut of a device. However, it is necessary to make the assumption that the spectral measurements that define the basis of the gamut, form an object whose surface is sufficiently convex in the spectral space. The convex hull is found by utilizing a convex hull algorithm, such as quickhull.[16]

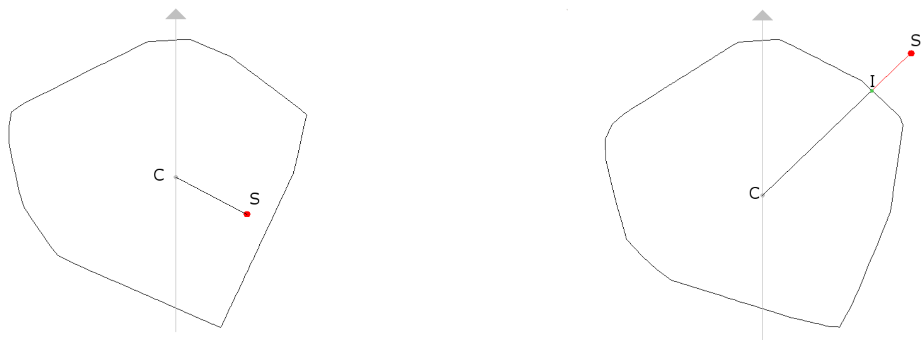
One of the issues concerning the choice of dimension when working with spectral reflectances, is the lack of a universal method for evaluating the differences between two spectra. This makes it difficult to set a reasonable threshold for accepting two spectra as sufficiently equal. Several metrics for evaluation of spectral match exist.[17–19] One commonly used metric is the spectral root-mean-square (RMS) error,

$$E_{\mathrm{RMS}} = \sqrt{\frac{1}{n}\sum_{j=1}^{n}(\Delta\beta(\lambda_j))^2} \quad , \tag{1}$$

where $\Delta\beta(\lambda_j)$ is the difference between the two spectra at wavelength λ_j. The advantage of this metric is that it is applied directly on the spectral reflectance curve of the spectra, and is therefore not valid under only one illuminant. An additional benefit is its linear response,[17] making it suitable for both small and large spectral differences. However, its failure to consider the properties of human vision regarding perceived color differences encourages the use of other metrics like CIELAB ΔE^*_{ab} in combination with this metric.

3. PROPOSED VISUALIZATION AND MAPPING METHODOLOGY

Due to the complexity of convex hull algorithms, a reduced number of dimensions must be used when the spectral gamut is calculated. In addition, the commonly used output devices have a limited number of colorants, which together with sources of error make exact reproduction of reflectances only possible for a small number of spectra, under a limited set of conditions. This restricts the value of a theoretical spectral gamut using full



(a) Spectrum inside gamut

(b) Spectrum outside gamut

Figure 1. Cross sections of the spectral gamut. An outline of the device gamut is displayed, along with the gamut center (C) and the position of two spectra (S) which should be reproduced. The intersection (I) between the gamut boundary and the line from the center to the reflectance is found.

(31-dimensional or similar) spectral dimensionality. By applying PCA to the data, a more manageable number of dimensions can be used.

In accordance with previous research,[8] we use a convex hull as the representation of the spectral device gamut. In addition to testing whether a given reflectance is within the spectral gamut of a device, we suggest a visualization of the gamut along with the position of the reflectance curve in the PCA-based space, in order to provide additional insight into the issues regarding spectral reproduction. Due to the limitations of visualization of high-dimensional objects, a cross section of the gamut is computed.

This cross section is the result of intersecting the gamut with a 2-dimensional plane. We suggest the use of a plane given by 2 vectors – a line between the given reflectance and the gamut center, and a vector representing the spectral gray component of the medium – as a relevant visualization, particularly when evaluating the reproducibility of a reflectance curve. The cross section of the gamut is found by calculating the intersection between the 2-dimensional plane and the hyperplanes that define the gamut. By finding the distance from the surface of the device gamut to the position of the reflectance, it is possible to give an indication of how much the reflectance must be changed in order to come inside the gamut.

We find this distance by calculating the intersection between a line from the center of the gamut to the given reflectance, and the hyperplanes that define the gamut surface. By moving from a point on the inside of the gamut towards the reflectance, the hyperplane intersection that is closest to the starting point indicates the transition to out-of-gamut space. Our implementation utilizes the method described here for finding the intersection between lines and the gamut, in order to find the outline of the gamut in the 2-dimensional plane that is relevant for visualization. This visualization is demonstrated in Figure 1.

This visualization suggests that it might be possible to perform a simple spectral gamut mapping algorithm on the reflectances. If a reflectance is on the outside of the gamut outline, one possible method of gamut mapping is to perform a clipping against the gamut surface towards a point on the inside of the gamut. Our suggestion is the use of the midpoint of the spectral gamut along each of the coordinate axes. This is the spectral equivalent to the conventional gamut mapping algorithm that performs clipping towards the center of CIELAB or a similar color space.

4. RESULTS AND DISCUSSION

We have added functionality for spectral analysis to the application ICC3D*, which already contains extensive possibilities for finding gamuts and applying gamut mapping algorithms in conventional 3-dimensional color spaces. The combination of existing methods for color management, and the support for spectral images and data, makes this tool useful in the process of examining issues regarding spectral gamuts and color reproduction. In order to provide the user with the possibility to perform analysis of spectral data, a variety of file formats and algorithms have been implemented. Multispectral test images in the MUSPEK multispectral image file format[20] have been used in our experiments, along with spectral reflectances taken from the Macbeth Color Checker, and spectral measurements of samples from a printer. The spectral data from these sources has been transformed to a common spectral format consisting of 31 sample values, ranging from 400 to 700 nm in 10 nm increments.

In order to construct a spectral device gamut, we have used spectral measurements taken from a HP Deskjet 1220c ink-jet printer. The color patches were measured with a GretagMacbeth Spectrolino spectrophotometer mounted on a Spectroscan XY table, and have previously been used for the spectral characterization of the device.[5] The MUSPEK spectral images contain 16 independent channels, and the 31-dimensional spectral reflectance curves have been reconstructed from this data.

By utilizing PCA on any the spectral data sets, PCA-based spaces have been constructed in which the actual mapping can be performed. In these experiments, spectral measurements of the printer have formed the basis for the creation of this reduction of dimensionality. This results in a transformation that maintains as much precision of the device samples as possible, giving a suitable starting point for the estimation of the spectral gamut.

The convex hull of the transformed spectral data from the device has been found by using the tool Qhull†. This has made the computation of convex hulls in spaces with a dimension of 3–8 possible, allowing a look at the impact that the choice of dimension has on the results of the mapping and visualization. Table 1 shows the time it takes to compute the convex hull of a number of input points. There is some overhead due to the interface layer in our application communicating with Qhull. The time consumption as well as the memory required to perform the calculations increase exponentially, making the use of more than 8–9 dimensions impractical on the computer hardware of today.

The spectral gamut is visualized by finding a cross section of its convex hull representation. As seen in Figure 1, this allows visual confirmation of the position of the reflectance compared with an outline of the spectral gamut in the PCA space. The reflectance in Figure 1(b) is positioned on the outside of the spectral gamut, and gamut mapping is therefore necessary to reproduce the reflectance on the given output device. The other reflectance in Figure 1(a) is clearly on the inside of the gamut boundary, and no mapping is required. The proposed method for spectral gamut mapping results in the reflectance in Figure 1(b) being moved to the point on the gamut surface where the line meets the gamut outline. The result is influenced by the spectral inaccuracy introduced by the PCA transform, as well as the spectral difference caused by the actual gamut mapping to the spectral gamut.

Table 1. Qhull time consumption in seconds.

Dimension	2	3	4	5	6	7	8
1000 points	0.141	0.141	0.141	0.156	0.266	0.594	2.641
2000 points	0.234	0.250	0.250	0.281	0.438	1.125	6.219
3000 points	0.422	0.453	0.453	0.485	0.734	1.579	10.121

*ICC3D (Interactive Color Correction in 3 Dimensions) is an application designed for the investigation of color gamuts and mapping algorithms in 3-dimensional color spaces. It is available from http://colorlab.hig.no/icc3d

†Qhull is an implementation of the quickhull convex hull algorithm. This tool is capable of calculating the convex hull of a set of points in space of arbitrary dimension. Further information is available at http://www.qhull.org/

Figure 2. An illustration of the original spectral image. The image is seen under the D65 illuminant, and the 2° standard observer is used to find the corresponding CIEXYZ tristimulus values of the reflectance curves. (Image courtesy of Patrick Herzog and Color AIXperts GmbH). Color images are available from http://colorlab.hig.no/icc3d/ .

Figure 3. An illustration of the spectral image after gamut mapping has been applied in a 4-dimensional PCA-based space.

We have applied the previously described method to several of the available spectral test images. One of the original images is illustrated in Figure 2, by utilizing the spectral power distribution of the D65 illuminant and the 2° standard observer.[21] The spectral image is changed by transforming the data to the PCA-space defined by the spectral printer measurements, and performing gamut mapping on the spectra. Figure 3 illustrates the result after performing the gamut mapping in a 4-dimensional space. The yellow areas are subject to substantial clipping, which correlates with a low number of device samples from this area of space. In order to achieve an optimal mapping, a larger number of device samples is clearly needed.

We have also observed the effect of the spectral GMA on the 24 spectral reflectances of the Macbeth Color Checker. Table 2 shows the average spectral RMS error of the spectra after PCA and GMA has been applied.

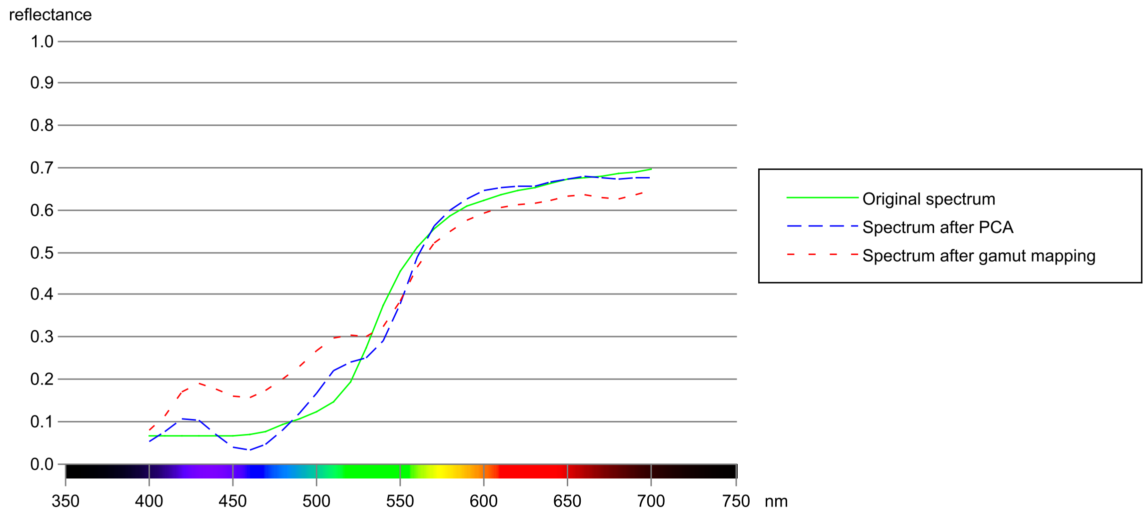


Figure 4. An illustration of a reflectance curve after gamut mapping has been applied in a 5-dimensional PCA space. The original spectrum is changed by the PCA transform as well as the gamut mapping.

The inaccuracy caused by the PCA transform clearly declines with the number of components used, while the RMS error after the mapping has been executed shows that the amount of clipping increases with the dimension. Figure 4 shows the result of performing PCA and clipping on a reflectance curve from the Macbeth Color Checker.

When applying this method, the result is heavily influenced by the choice of the point inside the gamut towards which the spectra are mapped. We have so far used the midpoint of the device gamut along each of the coordinate axes, which is an easy to find point that is inside the spectral gamut. Alsam[22] suggests that the center of a convex hull can be calculated by finding each coordinate that divides the convex hull into two objects with equal volume, which would likely give a better basis for both the visualization and the mapping algorithm.

5. CONCLUSIONS AND FUTURE WORK

We have introduced a method for spectral gamut mapping and visualization. By reducing the dimensionality of the data by applying PCA, and representing the spectra by a lower number of components, the convex hull of the spectral device measurements can be calculated. This object is used as an approximation of the spectral device gamut, and is the basis for our proposed mapping algorithm. By transforming spectral reflectances to the same PCA space, they can be compared to the gamut boundary. The cross section of the gamut in the plane defined by the gamut center, the position of the reflectance, and the vector representing the spectral medium gray is found. By comparing the position of the reflectance to the outline of the gamut in this plane, it is possible to determine the distance between a given reflectance and the point on the gamut surface in the direction of the center. Our clipping algorithm translates all reflectances outside the gamut along this line to the center, until the gamut surface is encountered.

Table 2. Average spectral RMS error of the Macbeth Color Checker reflectances. The RMS errors after PCA and GMA are found by comparing the reflectances to their original, unmodified values.

Dimension	2	3	4	5	6	7	8
E_{RMS} after PCA	0.067	0.037	0.030	0.025	0.021	0.020	0.018
E_{RMS} after GMA	0.072	0.058	0.060	0.078	0.071	0.068	0.088

Experiments show that the amount of clipping increases with the number of dimensions, and that the selection of enough spectral device measurements to cover the PCA-based space is crucial to the validity of the spectral gamut. A higher number of dimensions span a larger space, increasing the need for data points. A logical extension of this algorithm is to improve the choice of gamut center point. One alternative is to follow the procedure described by Alsam,[22] which should result in a point which is positioned at the center of mass of the device gamut.

The main advantage of this method compared to conventional GMAs, is that it can be applied to data in the spectral domain. GMAs that work in color spaces where distance is closely related to perceived color difference, have advantages when making decisions regarding the direction and amount of mapping to be done on images. The validity of convex hull as a representation of spectral gamuts is also an area of interest for further studies, since the effectiveness of a GMA depends on the suitability of the GBD. The practical application of spectral gamut mapping in the spectral workflow, represents a step towards better understanding of the issues regarding spectral image reproduction. The investigation of the effect of gamut mapping on an actual attempt at spectral image reproduction is necessary to make any conclusions regarding the practical value of this method.

ACKNOWLEDGMENTS

We would like to thank Patrick Herzog and Color AIXperts GmbH for the use of their spectral test images. We would also like to thank Jeremie Gerhardt for his spectral sample measurements taken from the HP Deskjet 1220 printer, used in order to generate the spectral device gamut.

REFERENCES

1. J. Y. Hardeberg, F. Schmitt, and H. Brettel, "Multispectral color image capture using a liquid crystal tunable filter," *Optical Engineering* **41**, pp. 2532–2548, Oct 2002.
2. F. H. Imai and R. S. Berns, "High-resolution multi-spectral image archives: a hybrid approach," in *Proceedings of the IS&T/SID's 6th Color Imaging Conference: Color Science, Systems and Applications*, pp. 224–227, 1998.
3. P. G. Herzog and F. König, "A spectral scanner in the quality control of fabrics manufacturing," in *Proceedings of the Conference on Color Imaging: Device-Independent Color, Color Hardcopy and Graphics Arts VI*, *SPIE Proceedings Series* **4300**, pp. 25–32, 2001.
4. M. Hauta-Kasari, K. Miyazawa, S. Toyooka, and J. Parrkinen, "Spectral vision system for measuring color images," *Journal of the Optical Society of America A* **16**(10), pp. 2352–2362, 1999.
5. J. Y. Hardeberg and J. Gerhardt, "Characterization of an eight colorant inkjet system for spectral color reproduction," in *Proceedings of CGIV 2004: the Second European Conference on Color in Graphics, Imaging, and Vision*, pp. 263–267, 2004.
6. L. A. Taplin and R. S. Berns, "Spectral color reproduction based on a six-color inkjet output system," in *Proceedings of the IS&T/SID's Ninth Color Imaging Conference: Color Science and Engineering, Systems, Technologies and Applications*, pp. 209–213, 2001.
7. D. Tzeng and R. S. Berns, "Spectral-based ink selection for multiple-ink printing i. colorant estimation of original objects," in *Proceedings of the IS&T/SID's Sixth Color Imaging Conference: Color Science, Systems and Applications*, pp. 106–111, 1998.
8. H. Haneishi and Y. Sakuda, "Representing Gamut of Spectral Reflectance by a Polyhedron in High Dimensional Space," in *Proceedings of the Third International Conference on Multispectral Color Science (MCS'01)*, pp. 5–8, 2001.
9. I. Farup, J. Y. Hardeberg, A. M. Bakke, S. Kopperud, and A. Rindal, "Visualization and Interactive Manipulation of Color Gamuts," in *Proceedings of the IS&T/SID's 10th Color Imaging Conference: Color Science and Engineering: Systems, Technologies, Applications*, pp. 250–255, 2002.
10. J. P. S. Parkkinen, J. Hallikainen, and T. Jaaskelainen, "Characteristic spectra of Munsell colors," *Journal of the Optical Society of America A* **6**, pp. 318–322, Feb 1989.
11. J. L. Dannemiller, "Spectral reflectance of natural objects: how many basis functions are necessary?," *Journal of the Optical Society of America A* **9**, pp. 507–515, Apr 1992.

12. J. Y. Hardeberg, "On the spectral dimensionality of object colours," in *Proceedings of CGIV 2002: the First European Conference on Color in Graphics, Imaging, and Vision*, pp. 492–496, 2002.
13. T. W. Anderson, "Asymptotic theory for principal component analysis," *Annals of Mathematical Statistics* **34**, pp. 122–148, 1963.
14. F. H. Imai, N. Tsumura, H. Haneishi, and Y. Miyake, "Principal component analysis of skin color and its application to colorimetric color reproduction on crt display and hardcopy," *The Journal of Imaging Science and Technology* **40**, pp. 422–430, Sep/Oct 1996.
15. J. Morovic and M. R. Luo, "The Fundamentals of Gamut Mapping: A Survey," *The Journal of Imaging Science and Technology* **45**(3), pp. 283–290, 2001.
16. C. B. Barber, D. P. Dobkin, and H. Huhdanpaa, "The quickhull algorithm for convex hulls," *ACM Transactions on Mathematical Software (TOMS)* **22**(4), pp. 469–483, 1996.
17. J. A. S. Viggiano, "A Numerical Comparison of Several Metrics for Spectral Match," in *Proceedings of CGIV 2004: the Second European Conference on Color in Graphics, Imaging, and Vision*, pp. 286–291, 2004.
18. F. H. Imai, M. R. Rosen, and R. S. Berns, "Comparative study of metrics for spectral match quality," in *Proceedings of CGIV 2002: the First European Conference on Color in Graphics, Imaging, and Vision*, pp. 492–496, 2002.
19. J. A. S. Viggiano, "A Perception-Referenced Method for Comparison of Radiance Ratio Spectra and its Application as an Index of Metamerism," in *Ninth Congress of International Colour Association, Proceedings of SPIE volume 4421 (AIC 2001 Proceedings)*, pp. 701–704, 2002.
20. P. Herzog, "MUSPEK Multispectral Image Format v. 1.4," 2004. Personal communication.
21. G. Wyszecki and W. S. Stiles, *Color Science: Concepts and Methods, Quantitative Data and Formulae*, John Wiley & Sons, 2nd ed., 1982.
22. A. Alsam, "Spectral camera calibration," in *Proceedings from Gjøvik Color Imaging Symposium 2003*, 2003.