A Color Gamut Visualization Tool

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Abstract

A computer graphic tool has been developed to help color scientists visualize the gamuts of color reproduction devices. Given the defining parameters of the media, the program can analytically determine the gamuts for color television monitors, color films, and paint pigments. Measured tristimulus values from specific devices can also be input. The program employs an algorithm to find the convex hull for gamuts defined from discrete data points. Gamut volumes and intersections are also determined using computational geometry techniques. To facilitate the comparison between alternative designs or between different color reproduction devices, several gamuts can be simultaneously displayed. The gamuts can be rotated and scaled in real time to create alternative views of the situation. A variety of computer graphic techniques such as smooth shading, color interpolation, and transparency are used to help the analyst make comparisons between the gamuts.

Introduction

Design and analysis of color reproduction equipment requires that the location and size of each device's color gamut be determined. The objective, in most cases, is to choose the monitor phosphors or the printing inks so as to maximize the size of the gamut and distribute the colors as uniformly as possible in color space. A number of different perceptually uniform color spaces have been developed to facilitate this task. Another problem that frequently occurs in the design of such equipment is a mismatch between the gamuts of color reproduction devices that must display the same color imagery. In this case it is necessary to determine the regions where the gamuts overlap and to devise schemes for approximating colors that lie outside the gamut of each device.

What will facilitate the design of such color reproduction equipment is a tool that allows the color scientist to visualize the color gamut of a proposed device. Given a set of color primaries or a collection of measured tristimulus values, the designer should be able to see the size and position in color space of the resulting color gamut. The effect on the color gamut of changing the television phosphors or printing inks should also be immediately apparent. To speed the analysis it must be possible to easily transform the color gamut into a variety of different perceptually uniform color spaces. These criteria demand that the visualization tool have a high degree of interactivity.

Computer graphics is the ideal way of providing such a color gamut visualization tool. Color is a three-dimensional quantity because each of the receptors in the human retina has one of three different spectral sensitivities. Color is therefore represented using a variety of different three dimensional coordinate systems. Computer graphics employs the power of the computer to create pictures of three dimensional scenes. Early computer graphics equipment was only capable of displaying wire line objects, but recently it has become possible to create full color images of three dimensional objects and to manipulate these solids in real time. Scientific visualization methodologies have also been developed to allow engineers to use computer graphics to analyze their data.[1,2] This makes computer graphic techniques and the high speed workstations on which they have been implemented the perfect vehicle for studying color and color spaces.

The Color Gamut Visualization Program (GAMVIS) is an interactive computer graphic program that has been developed to provide the designer of color reproduction equipment with such a tool. Two or more color gamuts for the same or different color reproduction equipment can be simultaneously displayed. This allows the analyst to explore how a change in the phosphors or printing inks will alter the color reproduction capabilities of the color television or color hard copy device that is being manufactured. There are several types of gamuts which can be created. Additive color reproduction devices such as color television monitors can be displayed if the colorimetric properties of their primaries are known. Given a set of filter transmittances, the subtractive gamut for a medium such as color film can be depicted. The GAMVIS program uses Kubelka-Munk theory to show the gamuts produced by mixing pigments. Finally, discrete data points can be read in to allow the analyst to examine a collection of measured tristimulus values from an existing color reproduction device.

Monitor Gamuts

An additive color reproduction device is represented in the GAMVIS program by using a monitor gamut. The colors visible on this device are generated by adding together the light from three sources. Typically these are the red, green, and blue (RGB) phosphors of a color television. The chromaticity coordinates of each phosphor, as well as the luminance and chromaticity coordinates of the white point, determine what color is shown when the phosphors are combined.[3] The gamut which results in CIE XYZ space from varying the luminances of the three phosphors in all possible combinations is a solid bounded by six planar quadrilateral surfaces.

To create a monitor gamut using the GAMVIS program, several parameters must be set on the relevant dialog box: the x and y chromaticity coordinates of each of the three monitor phosphors, the x and y chromaticity coordinates of the monitor white point, the luminance of the white
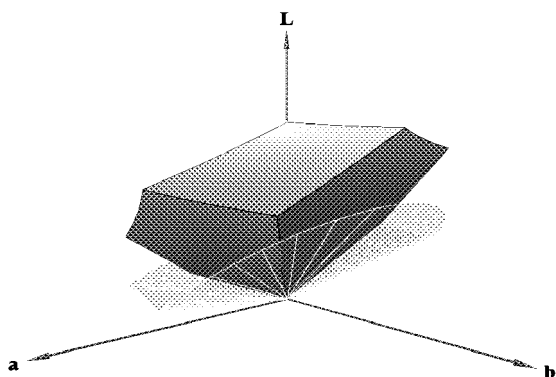
Figure 1. *Monitor gamut and cone of realizable color in CIE Lab space.*

point, the RGB increment, and the name of the new gamut. The RGB increment determines what values of R, G, and B are sampled to generate a discrete representation of the gamut. The name of the gamut is used to reference that gamut throughout the GAMVIS program. A typical monitor gamut representation produced by the program is shown in Fig. 1.

Filter Gamuts

Additive gamuts, like that of a television monitor, are built by adding together sources of light and varying their luminances. By contrast, subtractive gamuts are built by subtracting the light from a single light source by shining that source through a set of filters. The resulting color depends upon the light source, the transmittances of the filters at each wavelength of the light source, and the concentration (thickness) of the filters.[4]

The colors which can be produced by varying the luminance of a single light source form a straight line in CIE XYZ space. The chromaticity coordinates on each point of this line are the same, since only luminance is varying. However, if the concentration of a single filter is varied while shining a particular light source through that filter, the resulting colors form a curved line in CIE XYZ space. Not only does the luminance of this line increase as the concentration of the filter decreases, but the chromaticity coordinates vary as well.

The gamut of two filters, formed by altering what percentage of each filter is used to make up the combination of the filters and by varying the concentration of the combination, is a curved, leaf-shaped surface. The gamut of three filters is a curved, bulb-shaped volume that has a boundary formed by the three surfaces that result from the possible two filter combinations. By contrast, the monitor gamut is bounded by six planar quadrilateral surfaces in CIE XYZ space.

To create a subtractive gamut using the GAMVIS program, several parameters must be set on the relevant dialog box: the light source, the filters used, the starting concentration, the ending concentration, the number of concentrations, and the name of the new gamut. The light source is chosen from a set of predefined light sources. The filters are chosen from the files in a predefined directory, where each filter has a file containing its transmittance at

certain wavelengths. The starting and ending concentrations are the smallest and largest concentrations of the combined filters used to make up the gamut. The number of concentrations determines how many concentrations are used to sample the points which make up the gamut. The name of the gamut is used to reference that gamut throughout the program. Figure 2 shows a filter gamut produced by the GAMVIS program for a color slide film.
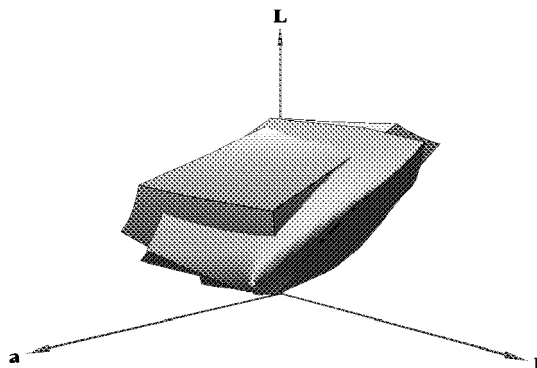

Figure 2. *Color film recorder gamut and color monitor gamut in CIE Lab space.*

Pigment Gamuts

Pigment gamuts are built by mixing together a set of pigments and shining a particular light source on the mixture. The GAMVIS program uses Kubelka-Munk theory to determine the color of a pigment mixture. This color depends upon the light source and the absorption and scattering properties of the pigments at each wavelength of the light source.[5,6,7]

Given a light source and a single pigment, there is only one color which can be produced, since the color does not depend on the quantity of the pigment. Therefore, the gamut of a single pigment is a single point. However, if a second pigment is added and the percentage of each pigment used in the mixture is varied, the resulting colors form a curved line in CIE XYZ space. The endpoints of this line are the single pigment gamuts. The gamut of three pigments forms a triangular, curved surface where each of the vertices is the gamut of one of the pigments. Adding a fourth pigment expands the surface into a pyramidal, curved solid. The four surfaces bounding this solid are the gamuts of the possible three pigment combinations.

To create a pigment gamut using the GAMVIS program, several parameters must be set on the relevant dialog box: the light source, the pigments used, the number of mixtures, and the name of the new gamut. The light source is chosen from a set of predefined light sources. The pigments are chosen from the files in a predefined directory, where each pigment has a file containing its coefficients of absorption and scatter at certain wavelengths. The number of mixtures determines how many different mixtures are used to sample the points which make up the gamut, where mixtures differ by what percentage of each pigment they contain. The name of the gamut is used to reference that gamut throughout the program.

Figure 3 shows a pigment gamut that was produced using the GAMVIS program. Alizarin red, cadmium yellow, prussian blue, and titanium white are the four pigments that were mixed to produce the gamut. It should be noted that mixing the red, yellow, and blue pigments but not the white pigment produces only the bottom most surface of the pigment gamut shown in Figure 3. It is the addition of the white pigment that generates most of the volume of the gamut.
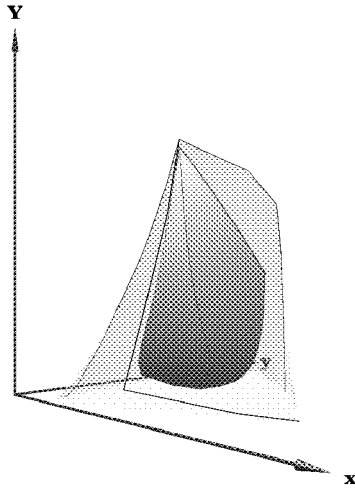

Figure 3. Pigment gamut and color film gamut in CIE Yxy space.

Comparing Gamuts

Because two or more color gamuts can be displayed simultaneously, the GAMVIS program can be used to compare the color reproduction capabilities of different pieces of equipment. By observing where the surface of one gamut lies in relationship to the surface of another gamut, the user can identify colors from one piece of equipment that cannot be reproduced on a second piece of equipment. The design of the hardware might then be adjusted so that its gamut is a better fit to another gamut.

The first gamut comparison example involves the gamut of a color monitor and the gamut of a film recorder which is being used to produce color slides of images displayed on the monitor. By creating both gamuts and then changing the representation used to display each gamut, it is possible to see what monitor colors cannot be reproduced by the film recorder. The monitor and film recorder gamuts are initially represented by smooth, colored surfaces, but these surface can also be drawn in a single color or transparently. The gamuts can also be represented as discrete point markers or not displayed at all.

With the film recorder gamut being displayed monochromaticly and the monitor gamut being displayed using continous color (see Figure 2), it is easier to see what colors the monitor is able to display which cannot be reproduced by the film recorder. The portions of the monitor gamut which are the most red, green, and blue stick out of the film recorder gamut. That the monitor gamut would be better at reproducing these colors is to be expected, since the monitor gamut is built using red,

green, and blue phosphors while the film recorder gamut is based on cyan, magenta, and yellow filters. The representation types of the two gamuts can also be switched making it is easier to see which colors the film recorder can reproduce which the monitor can't.

In the second example, the pigment gamut produced by mixing alizarin red, cadmium yellow, prussian blue, and titanium white is compared with the film recorder gamut. The problem in this case is that the pigment gamut is relatively small and lies completely within the film recorder gamut. In order to see both gamuts simultaneously it is necessary to represent the film recorder gamut transparently. The result is shown in Figure 3.

Discrete Gamuts

Instead of being derived by using a particular theory, the discrete gamut is defined by a set of points which are read from a file. This is useful for viewing the gamut of a piece of color reproduction equipment for which a set of tristimulus values has been measured.

As well as representing a discrete gamut by a set of points, the GAMVIS program can generate a surface representation for each discrete gamut when it is created. The surface representation that is calculated is the convex hull of the set of points, which is the surface that most tightly fits the points without having any indentations. Although this is only an approximation to the surface of the actual gamut, the convex hull does clarify what space is occupied by the points.

While gamuts are displayed using discrete representations, certain operations can be performed on them. A subset of gamut points can be selected and a new gamut can be created from those points. By creating a subset, a slice into a single gamut can be shown. Certain operations can be performed on the convex hulls of discrete gamuts as well. Binary operations such as intersection and difference can be performed between two convex hulls. The volume of a convex hull can also be calculated.

Subsets of Discrete Gamuts

Before creating a subset of a gamut which is displayed using a discrete representation, a set of points from the gamut must be selected. Points can either be chosen using the mouse in the display area or by entering, on a dialog box, an equation of the coordinate values of the selected points. The currently selected points are then the points that make up a subset when one is created.

To select points using a mouse, the mouse button is pushed down in the display area, the mouse is dragged to another location, and the button is released. While the mouse is being dragged, the cursor becomes a rectangle whose opposite corners are the location where the button was pushed down and the current location. When the mouse button is released, all points whose markers were drawn within the last rectangle shown are selected.

Points can be selected more precisely from their coordinate values by constructing a boolean equation. For example, entering the text **L > 55.0 and L < 75.0** in the proper window selects all points of the gamut whose L coordinate value is greater than 55.0 and less than 75.0. Points can also be selected by comparing two coordinate

values to each other. In fact, any set of points that is bounded by planes can be selected, even disjoint sets. For example, the points of the gamut that are not currently selected can be selected instead by entering the negation of the above equation.

Once a set of points has been selected, a subset can be created from those points. The new subset is also a discrete gamut, so the same operations which can be performed on a discrete gamut can be performed on a subset. In particular, a subset can be displayed with the same representation types as a discrete gamut. A subset of the subset can also be created.

Comparing Discrete Subsets

Subsets of gamuts can be used to better compare the difference in the color reproduction capabilities of devices. By slicing up gamuts, it is easier to see where significant differences occur between them. In Figure 4 the above equation has been applied to the gamut of a color monitor and a color printer.
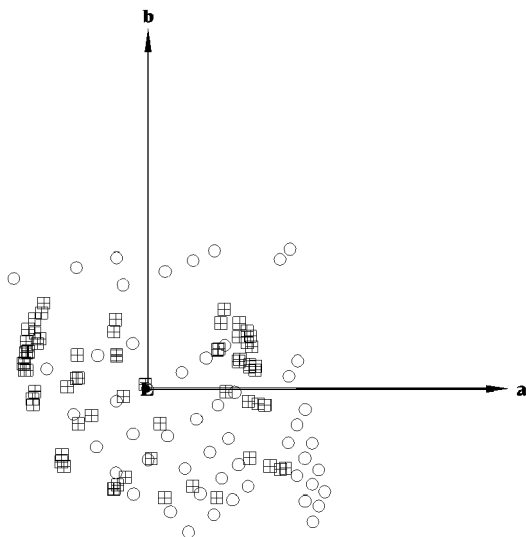

Figure 4. Monitor gamut (circles) and printer gamut (crossed squares) in CIE Lab space.

By looking down the L axis, you can see the difference in the colors reproduced by the monitor and the printer in the range of L values described in the equation used to select the gamut points. For the most part, the two subsets have points in the same area near the axis. However, the monitor has points extending beyond the printer in the red area while the printer subset has points extending beyond the monitor subset in the cyan area. Both gamuts extend beyond each other at different areas of green and blue.

Since red is one of the phosphors on which the colors of a monitor are based, it is not surprising that there would be more red points in the monitor gamut. Similarly, since cyan is one of the primary dyes used by the printer, it might be expected to produce more cyan colors. It is interesting to note that the printer gamut does not extend farther in the direction of yellow or magenta, since these are also primary colors for that gamut.

Convex Hulls

When gamuts are created from a set of discrete points, a surface representation is generated. The surface representation used by the GAMVIS program is the convex hull of the set of points, which is the surface that most tightly fits the points without having any indentations. The convex hull is an approximation to the surface of the gamut defined by the set of points, since it depends on which points of the gamut have been included in the set. However, it does help show what volume is occupied by those points.

In Figure 5 the convex hulls of the above two discrete gamuts are compared as another way to view the difference in color reproduction capabilities of the corresponding devices. By looking at the gamuts, you can see where the multi-colored convex hull of the printer gamut extends beyond the transparent convex hull of the monitor gamut. These are the colors that the printer can reproduce but the monitor can't. The printer gamut has more colors near two of its primaries: cyan and yellow. However, the magenta portion of the printer gamut lies inside the monitor gamut.
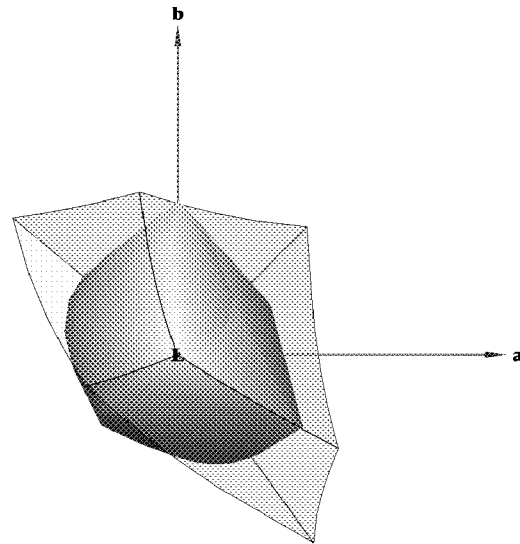

Figure 5. Monitor gamut (transparent) and printer gamut (multi-colored) in CIE Lab space.

Since the monitor gamut extends as far as or further than the printer gamut from the L axis at all color areas except cyan, the monitor can produce more saturated colors than the printer for most hues. Note that although the printer gamut extends beyond the monitor gamut near its yellow primary, it extends above the monitor gamut to a higher luminance value but not any farther away from the L axis than the monitor gamut. Note also that the part of the printer gamut near its magenta primary is surprisingly far inside the monitor gamut.

Binary Operations between Convex Hulls

Computational geometry techniques[8] can be used to find the convex hull (or hulls) of the intersection or difference of two convex hulls. The points of the convex hull of the intersection of the above printer and monitor convex hulls were calculated using a separate program.

The surface representation of this new gamut is the convex hull of the intersection of the printer and monitor convex hulls. In Figure 6 one can see that the intersection gamut is the largest solid lying inside both the printer and the monitor gamuts.
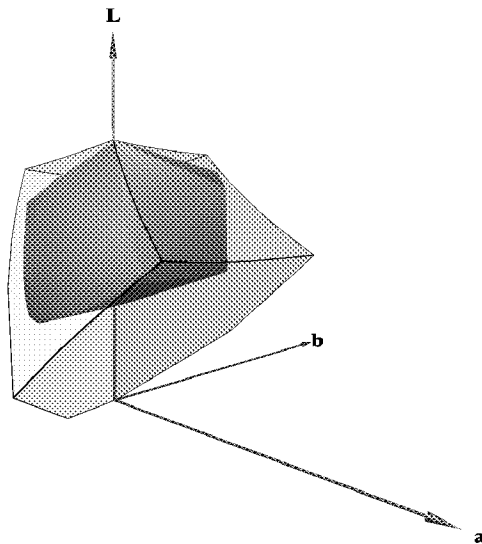

Figure 6. Monitor gamut (transparent) and intersection between printer gamut and monitor gamut (colored) in CIE Lab space.

Gamut Volumes

The volume of the surface representation of a gamut is calculated for each color space when that gamut is created. The volume of a gamut is calculated using a simple algorithm which breaks the gamut solid into tetrahedrons, where the base of each tetrahedron lies on the surface of the gamut and the top of each tetrahedron is the same inner point for all tetrahedrons. The volume is then the sum of the volumes of all the tetrahedrons.

By comparing the volumes of the defined gamuts, it can be seen that the volume of the intersection gamut is smaller than the volume of either the monitor or the printer gamut. This should be the case since neither the monitor nor the printer gamut is entirely contained in the other gamut. The volumes of other gamuts not created can be calculated from the values that are known. For example, the volume of the difference of the monitor convex hull and the intersection convex hull can be found by subtracting the volume of the intersection gamut from the volume of the monitor gamut.

Acknowledgements

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