

New gamut boundary target for defining the colour gamut of a printing system

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Abstract

A new test target for defining the gamut boundary of a printing device is described, which results in a list of vertices on the boundary and the set of triangular faces that connect them. When used in conjunction with an ICC profile for the device in a procedure to compute the gamut volume, this target is shown to give highly-reproducible estimates independently of the CMM. A method of identifying irregularities in the gamut surface is described. Results are shown for a wide range of printers, both for conventional and digital ink-jet systems.

Introduction

The colour gamut of a reproduction system is typically described in terms of a set of points known to lie on the gamut surface (vertices). A formal gamut boundary descriptor may connect these points in a variety of different ways. One such method that is increasingly adopted [1, 2, 3] is an array of planar faces that connect the vertices. For the method described here the planar faces are triangles. This way of encoding the gamut does not presuppose any particular method for generating either the vertex array or the faces.

For a printing system, its colour gamut is a critical property that determines whether it will be able to reproduce the required range of colours. For a given colour, it is generally possible to determine whether it lies inside or outside a gamut boundary computationally or by inspection. However, it is also useful to be able to describe the gamut in general terms, such as the volume or the proportion of a reference gamut that it will reproduce. When comparing two gamuts, it is necessary to know both the volumes of the individual gamuts and the intersection common to both [4].

In order to communicate a gamut boundary for the purposes of comparison and evaluation it is desirable that the gamut boundary description is reproducible, in the sense that the same characterization data always leads to a description of the gamut which gives consistent results when used to define its volume and the location of the volume in colour space. It should also be simple, so that any user can easily generate the boundary description from characterization data or ICC profiles.

When the gamut boundary is described as a triangulated surface, given a set of coordinates in colour space, the volume can be determined by adding a point within the gamut and connecting each triangular face to this point to form a tetrahedron [5]. The volume of each tetrahedron is computed using eqn. 1, and the volumes of all the tetrahedra are summed to give the gamut volume.

$$V = |a \cdot (b \times c)|/6 \quad (1)$$

where a, b and c are the vectors connecting each of the three vertices of the triangle on the gamut boundary to a fixed centre point inside the gamut.

For this procedure to return an accurate value for the volume the conditions are that the faces are non-overlapping and there are no gaps between them. An advantage of the face/vertex encoding is that any set of arbitrary points on the surface can be connected to form a gamut boundary. However, meeting the above conditions when triangulating an arbitrary set of points can be a challenge. Since printer gamuts are invariably non-convex in shape, a convex hull triangulation is expected to produce an over-estimate of the gamut volume, while a Delaunay triangulation (using Qhull [6]) often fails to connect the faces in a way that satisfies the conditions above. The alpha shapes method [7] does not suffer this problem, nor does SMGBD [8] which generates a regular boundary description from characterization data; however it is desirable to have a method that can compute both device and addressable gamuts from a device profile.

Triangulation problems can be minimized by defining a regular mesh and fitting this to the gamut surface. A mesh can be defined in colour space and then mapped to the surface, or it can be defined as a regular array of coordinates in device space which have the property of being on the colorant surface (i.e. one or more of the primaries has a value of 0 or maximum at all L* lightness values above the cusp, with the same conditions at L* values below the cusp with the addition of black). A gamut boundary target was previously proposed for this purpose [9]. This target, shown in Figure 1, was formed with 18 columns and 24 rows, where in each column the ratio of colorant combinations is constant and the amounts of colorant progressively increases. Thus the target approximates hue in the horizontal dimension and lightness in the vertical dimension.

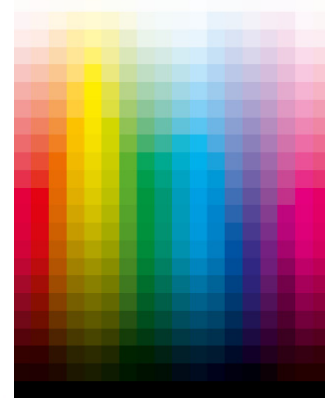


Figure 1. CMYK gamut boundary target [9]

The target was primarily designed for use in gamut mapping, and it has a higher frequency of spacing in the vertical dimension around the gamut cusp in order to obtain precise information about the cusp. In testing [10] it was found this target gave good results,

but in subsequent analysis it was found that for some data sets a number of faces, when mapped into colour space, do not satisfy the non-overlapping condition and some small faces not readily visible by inspection are not correctly oriented.

Gamut boundary considerations for CMYK printers

Some issues in encoding the gamut boundary are discussed below.

Device gamut vs addressable gamut

Printer characterization data is obtained by printing and measuring a set of coloured patches whose colour is specified in device coordinates (colorant amount). Available test charts for this purpose (e.g. [11, 12]) are not restricted by considerations of the total ink limit which is generally applied to a given process. The gamut surface derived in this way can be considered to be the gamut of the printing condition (printing device, substrate, inks and print settings) for which it was characterized. This is often called the device gamut.

In practical use, total ink limit restrictions prevent certain colorant combinations being printed, for example to avoid set-off and marking or to limit ink usage. These restrictions are defined through choices made in the colour separation, which are in turn encoded in the BToA look-up tables in the printer ICC profile. The colorant gamut which can be addressed in a given workflow can be determined by applying the BToA transform to colour space coordinates on the device gamut boundary. This is often called the addressable gamut.

Triangulation

A requirement of a gamut encoding procedure is that the vertices should be listed in clockwise order when viewed from outside the gamut [10]. The set of faces must also form a closed polyhedron with no gaps or overlaps. Euler's formula can be used to verify that the faces connect correctly, where the Euler number is 2 for a simplicial polyhedron. It can also be noted that in such a closed polyhedron, each edge in a face is common to one other face. An example of incorrectly triangulated points is shown in Figure 2.

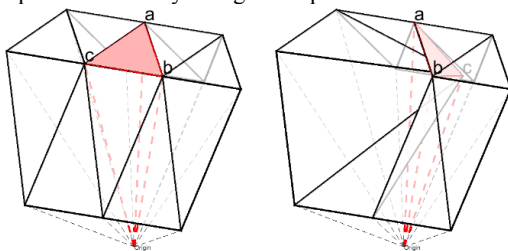


Figure 2. Vertices abc triangulated correctly (left) and incorrectly (right)

Owing to the difficulty in ensuring that these requirements are met for every face, it is useful to have a method to identify incorrectly-triangulated faces and the magnitude of their effect on the total volume calculation. Such methods are considered below.

Volume calculation

As noted in [4], the numerator in Eqn 1 is the scalar triple product of the three vectors, a property of which is that V is invariant with a circular shift of the vertices as long as the winding order is

maintained, but the sign of V is changed if the order changes, i.e. $a \cdot (b \times c) = c \cdot (a \times b)$ but $a \cdot (c \times b) = -a \cdot (b \times c)$

If the sign of V_i changes, $\sum |V_i|$ is likely to be incorrect as negative V_i indicates that the vertices have become misaligned and the resulting face will overlap with other faces. Negative V_i can thus be used as a test for incorrect orientation of the faces.

Since the total solid angle subtending from a point into the overlying sphere is 4π steradians, an additional test for the triangulation is to compute the solid angle Ω of each tetrahedron and compare the sum to 4π . The difference between 4π and $\sum \Omega_i$ is denoted $\Delta\Omega$.

New gamut boundary target

A new target is proposed which seeks to minimize the number of incorrectly-defined faces and achieve a more robust boundary descriptor. The target is similar in layout to [9], but was created in uniform hue and lightness steps in an RGB image in Photoshop and converted directly to CMYK. The greater uniformity of spacing of vertices and faces in colorant space can be seen in Figure 3.

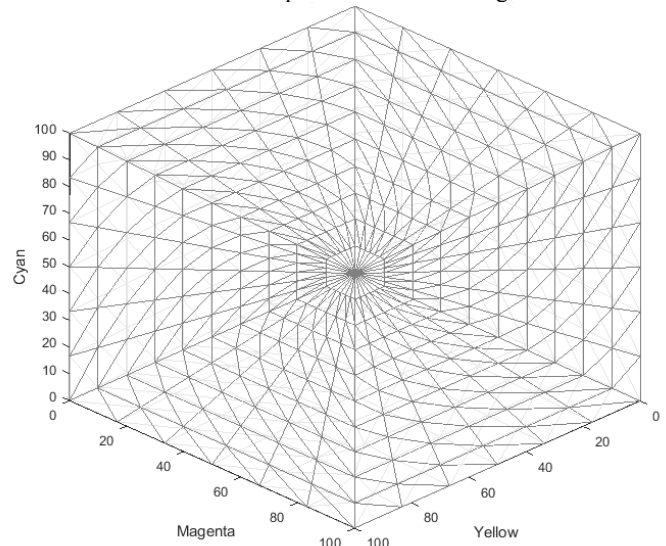


Figure 3. Projection on a^* , b^* for the proposed gamut boundary target, and associated triangulation.

The proposed target is shown in Figure 4 (CMYK values simulated).

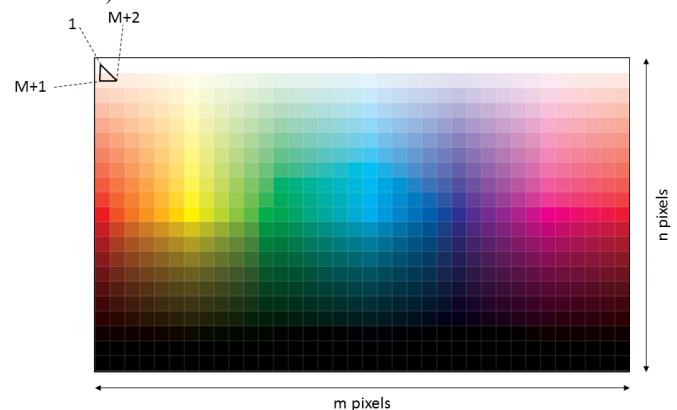


Figure 4. Proposed CMYK gamut boundary target

A face array (i.e. the indices into the vertex array) for this $n \times m$ target was constructed starting with the upper left device coordinate, and adding the two coordinates in the next row in clockwise order. The first face (encoded as the first entry of the faces list) is therefore $[1, m+2, m+1]$. The next face is $[1, 2, m+2]$; and the remainder of the face array was generated by moving through the device coordinates in the same manner.

Evaluation

Following on from the work reported in [10], testing was performed with the proposed new target. 16 publicly-available characterization data sets [13] and reference profiles [14] were used in one phase, and in a second phase 32 data sets and profiles for a range of media on HP ink jet printers and presses were used. Measurement data in all cases was given in CIELAB coordinates for the CIE D50 illuminant and CIE 1931 standard colorimetric observer. Although most of the media contained fluorescent whitening agents the effect of fluorescence was not considered relevant and no adjustments were made to compensate for UV inclusion or exclusion.

The gamut boundary for each profile was determined using the procedure in [10]. To obtain the device gamut, the target was converted from CMYK to CIELAB colour space, using the profile as the source and a D50 CIELAB profile (PCS identity) as the destination. To obtain the addressable gamut, a further round trip was performed whereby the device gamut coordinates were transformed back to CMYK, and then again back to CIELAB, using the same profile as for the device gamut and using the ICC-Absolute Colorimetric rendering intent throughout. This procedure to obtain colorimetric coordinates of the gamut vertices was performed in Matlab using the `makeform` and `applycform` functions in the Image Processing Toolbox, and repeated in Adobe Photoshop CS as a cross-check. Reading the image colorimetric data row-wise generates the vertex array, and the face array described above was used to define the triangulation, with an additional point at $[50,0,0]$ to form the tetrahedra array. The gamut volume for each data set was then calculated from the colorimetric coordinates of the tetrahedra array according to Eqn 1.

We note that for some colour gamuts a more consistent result can be obtained using a point midway between the white point and black point of the ICC Profile rather than a fixed point of $[50,0,0]$.

As an independent check of the results, the volumes were also calculated using the alpha shapes method [7], with a radius of 40.

Results

The results are shown in Table 1 in terms of the proportion of the gamut volume.

Table 1. Results for reference and ink jet profiles

| | Ref profiles | Ink jet profiles |
|---|--------------|------------------|
| Proportion of device gamuts that include incorrectly-oriented faces | 0.19 | 0.66 |
| Device gamut mean ΔV | 0.0004 | 0.0002 |
| Device gamut max ΔV | 0.0047 | 0.0006 |

| | | |
|--|--------|--------|
| Proportion of addressable gamuts that include incorrect faces | 0.31 | 0.75 |
| Addressable gamut mean ΔV | 0.0003 | 0.0011 |
| Addressable gamut max ΔV | 0.0023 | 0.0130 |
| Mean disagreement between Matlab and Photoshop methods: device gamut | 0.0001 | 0.0001 |
| Mean disagreement between Matlab and Photoshop methods: addressable gamut | 0.0026 | 0.0036 |
| Difference between device gamut computed by the method and by alpha shapes | 0.0019 | 0.0056 |
| Device gamut mean $\Delta \Omega$ | 0.0031 | 0.0010 |
| Addressable gamut mean $\Delta \Omega$ | 0.0018 | 0.0025 |

The results indicate that although a significant number of device gamuts determined as described above include incorrectly-oriented faces, the effect on the estimated gamut volume is negligible and in most cases is below 1%. The results also suggest that there is a high level of agreement between the results, regardless of the software used to perform the profile conversions. The small differences in the table between results obtained using MATLAB and Photoshop are thought to arise from the different CMMs used in these products.

Conclusions

When used to define the gamut boundary of CMYK printers and calculate the resulting volume, the proposed gamut boundary target produces consistent results regardless of the computational environment. The resulting device gamut volumes agree well with those computed using the alpha shapes method, and the method can also be used to determine the addressable gamut of a printer with total ink limitations.

A negative sign in the triple cross product when computing tetrahedron volume is an indicator of an incorrectly-oriented face. For a total gamut volume the $\Delta \Omega$ metric is an approximate indicator of the contribution of incorrectly-oriented faces.

This paper has focused on CMYK printers. For an RGB device there is normally no distinction between the device gamut and the addressable gamut, so the methods described here for the device gamut are applicable. For an n-colour printing system the same principle could be used to derive a boundary target and associated face array as for the CMYK target described here although the construction of such a target has not yet been done and is likely to be more complex.

A face array determined by the procedure described above is available [15], together with the proposed gamut target. The face array and vertex array are consistent with the `gamutBoundaryDescriptorTag` used to encode a gamut boundary in ICC.2:2017 [1].

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