Colour Gamut Mapping for Ultra-HD TV

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1 ABSTRACT

After the introduction of the new standard REC.2020 by the International Telecommunication Union (ITU) [1], the most pressing issue regarding colour reproduction has been backward compatibility; content recorded in the new wide colour gamut (WCG) cannot be faithfully represented in HDTVs due to the smaller gamut defined in REC.709 [2], to which HDTVs are compliant. In a few years' time, broadcasting companies will transmit TV programs using the more visually pleasing WCG, and consumers that possess an HDTV will not be able to experience the content unless the colours are mapped back to the REC.709 gamut.

The main aims of this project are to (i) identify the principal issues relating to the conversion between the new UHDTV and the old HDTV gamuts, focusing on the downgrade in order to tackle backward compatibility; (ii) investigate previous work relevant to this problem and apply the most suitable Gamut Mapping Algorithms (GMAs) to this specific case study; (iii) explore new algorithms to perform colour gamut conversion, designing them to work specifically for the REC.2020 and to; (iv) have a group of people perform subjective evaluation on both previous and new solutions.

2 GAMUT MAPPING ALGORITHMS

2.1 Established methods – RGB Scaling

This method consists of a direct conversion of the original YUV image to HD in the RGB format by using a conversion matrix obtained reversing the coefficients indicated in REC.709.

$$RGB_{709} = \begin{matrix} 1 & 0 & 1.5748 \\ 1 & -0.1873 & -0.4681 \\ 1 & 1.8556 & 0 \end{matrix} \; YUV_{2020} \qquad (1)$$

The first result obtained will have some colours that are not legal (i.e. RGB values below 0 or beyond 255 when using 8 bit images). Pixels with negative RGB values are clipped to 0 in order to preserve the darkest areas of the image, which would be brightened if the values were scaled up. After that, all the RGB components are scaled down with respect to the maximum achievable value of the same component (i.e. Max_R = 287.95, Max_G = 278.31, Max_B = 278.28 for 8-bit images). This linear scaling will legalise all out-of-gamut colours, but at the same time it will reduce the lightness and chroma of all the colours that were already inside the HD gamut, leading to a washed out image.

2.2 Established methods – HPMINDE (CIE obligatory method)

The acronym of this method stands for Hue Preserving Minimum ΔE [3], where ΔE is a distance measure performed in the CIELAB colour space. This method is usually referred to as minimum colour difference, and consists of maintaining unchanged any colour that is already inside the destination gamut, while mapping the out-of-gamut colours to the nearest point inside the destination gamut. This method essentially results in clipping to the destination gamut boundary, often leading to artefacts where multiple colours map to a single point.

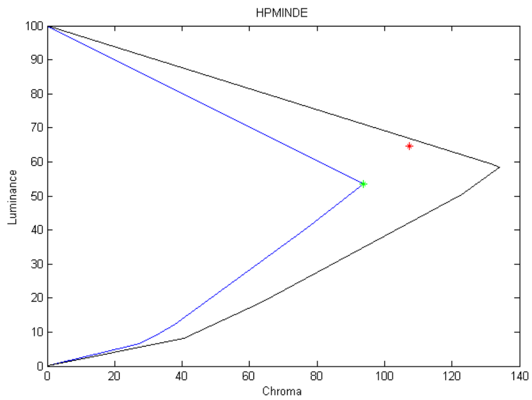

Figure 1 - A mapping example using HPMINDE. The black boundary represents the REC.2020 gamut, while the blue one represents the 709 gamut. The red point is mapped towards the green point.

2.3 Established methods – SGCK (CIE obligatory method)

As for HPMINDE, SGCK is an obligatory method for benchmarking as indicated by CIE in "Guidelines for GMA evaluation" [4]. SGCK is also called "Chroma-dependent sigmoidal lightness mapping and cusp knee scaling", and it is a combination of two methods: GCUSP [5] and "Sigmoidal lightness mapping and cusp knee scaling" [6]. It can be summarised in the following steps: the image is first converted in CIELAB space, and more precisely in Lch, where the three axes of the space represent luminance, chroma and hue (Colour space conversions are fully describe in the following chapter). The hue is maintained constant and only the chroma and luminance are affected by the mapping, which is made towards the projection of the destination gamut's cusp on the lightness axis. The process is shown in figure 2:

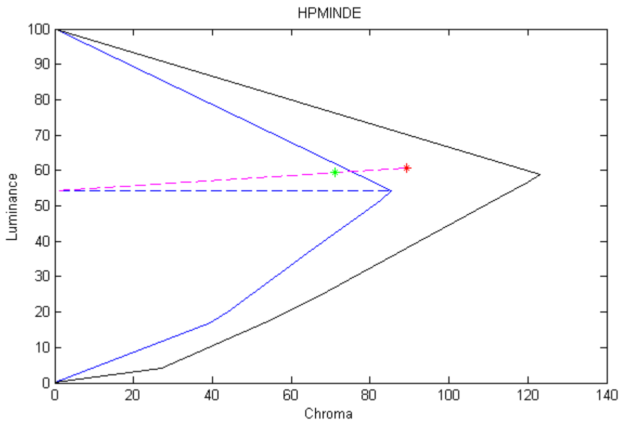

Figure 2 - SGCK Mapping example. The black boundary represents the source gamut, while the blue one represents the destination gamut. The red point is the original colour.

The converted point will lay on the line that connects the projection of the cusp on the luminance axis (hereby E) and the point representing the original colour. The distance from point E of the converted point is calculated as follows:

$$d = \begin{cases} d_o & ; d_o \leq 0.9\, d_{gr} \\ 0.9\, d_{gr} + \dfrac{d_o - 0.9\, d_{gr} \quad 0.1\, d_{gr}}{d_{go} - 0.9\, d_{gr}} & ; d_o > 0.9\, d_{gr} \end{cases} \qquad (2)$$

where d_o is the distance between the original point and E, d_{gr} is the distance between E and the destination gamut boundary (on the line that connects E to the original point) and d_{go} is the distance between E and the source gamut boundary (on the line that connects E to the original point).

By applying this method, both the luminance and the chroma are converted, resulting in a slightly darker colour when the original pixel is brighter than the cusp at that hue and vice versa in a slightly brighter colour when the original pixel is darker than the cusp.

2.4 Proposed methods – “UHD RGB Coefficients”

In this method, the UHD image is first converted from YUV format to RGB by following the procedure explained in the colour-space conversion section. This is performed by using the correct matrix to convert an image which is originally from the REC.2020 gamut. Once the image has been converted to RGB, it is then considered to be an image in the REC.709 gamut and thus converted back to YUV format. This procedure ensures that all colours in the final image will be legal because during the first conversion all resulting RGB components will be in the range 0 – 255 (for 8 bit images).

2.5 Proposed methods – Inverse REC.2087

As mentioned in the expansion GMAs section, ITU recently published a recommendation to convert HD content to UHD by either keeping the same colours, as all colours inside the REC.709 gamut are inside the REC.2020 gamut, or enhancing them in order to exploit all the UHD gamut. This recommendation is called REC.2087 [7], and this method is aimed at inverting the steps there described to perform the opposite conversion. In particular, the conversion where the full REC.2020 gamut is used is taken into consideration because the original image may take advantage of all the UHD gamut. The following operations are performed:

- The image is converted to RGB as normal
- The RGB values obtained are gamma corrected by being elevated to the power of 2
- The following matrix is used to convert the image:

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix}_{709} = \begin{pmatrix} 1.6605 & -0.5877 & -0.0728 \\ -0.1246 & 1.133 & -0.0084 \\ -0.0182 & -0.1006 & 1.1187 \end{pmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix}_{2020} \quad (3)$$

  The matrix was obtained by reversing the one contained in REC.2087, there used to perform the opposite conversion:

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix}_{2020} = \begin{pmatrix} 0.6274 & 0.3293 & 0.0433 \\ 0.0691 & 0.9195 & 0.0114 \\ 0.0164 & 0.088 & 0.8956 \end{pmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix}_{709} \quad (4)$$

- The values obtained are then gamma corrected again by square rooting them
- The conversion to YUV format is then performed as normal for HD images

2.6 Proposed methods – Hue Lightness Preserving Chroma Mapping

Finally, the last method that was implemented was HLPCM (Hue Lightness Preserving Chroma Mapping). This method is incremental on previous state of the art methods. However, it takes into consideration the characteristics of REC.709 and REC.2020 gamuts, performing a conversion specifically suited to these gamuts. In particular, the two gamuts have the same range of luminance (the reference white is D65 in both HD and UHD gamuts).

The goal of this method is to maintain chroma difference while keeping the image as similar as possible to the original. For this reason, only chroma is mapped, while luminance and hue are maintained constant. Furthermore, the source colour is not mapped if its chroma is below 30% of the maximum UHD gamut chroma attainable at said hue and luminance. This results in the least saturated colours inside the REC.2020 gamut being maintained constant when down-converting to HD, while the remaining, more saturated colours are mapped using a knee function towards the remaining chroma values inside the REC.709 gamut.

The following formula is used to map chroma:

$$C_{709} = \begin{cases} C_{2020} & ; C_{2020} \leq Lc \\ Lc + 4\,(Max(C_{709}) - Lc)(\sigma - \sigma^2) & ; C_{2020} > Lc \end{cases} \tag{5}$$

$$\sigma = \frac{C_{2020} - Lc}{2\,|Max(C_{2020}) - Lc|} \tag{6}$$

where Lc indicates 30% of the maximum chroma at the source colour's hue and luminance and Max(C) represents the maximum chroma for each gamut. In the next figure the function is plotted to display how it works:

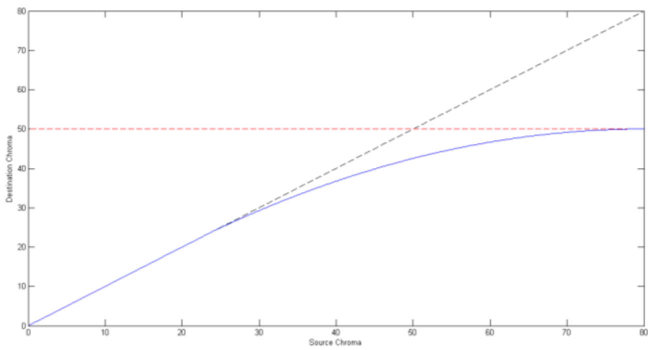

Figure 3 - Illustration of the results of the knee function .

In the figure, the blue line represents the mapping function, the red line indicates the maximum value on the destination chroma, and the black line shows the value of the source chroma if they were not mapped. It appears clear that some sort of clipping would have to take place at the destination gamut maximum chroma. However, with this method, a relative distance between the colours is maintained and soft clipping is performed without mapping several colours to a single point as in HPMINDE.

An example is shown in the following figure:

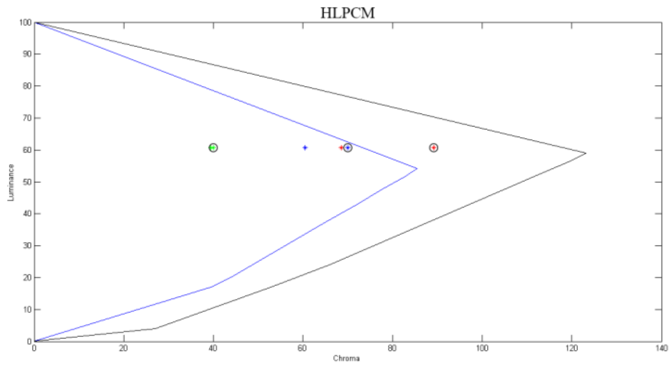

Figure 4 - Illustration of three colours being mapped using HLPCM.

In the figure above, three colours with the same luminance and hue are mapped from the UHD gamut (shown in black) to the HD gamut (shown in blue). The circled points represent the source colours, and corresponding points are coloured in the same way. It can be observed that the difference between the red coloured points is quite large, while the blue point, which has a significantly lower chroma, is mapped to a point much nearer to it. The green coloured source point, instead, can hardly be distinguished by the destination point due to its short distance to Lc, where the colours are maintained constant.

3 EXPERIMENTS

3.1 Perceptual evaluation

The dataset used during the experiments and some of the results obtained from the conversions are shown in the appendices. The evaluation was performed subjectively, two separate sessions were conducted on two different populations: a group of 17 students from different courses and a group of 17 collaborators working at InSync Ltd. The participants' age was in a range between 19 and 64 years and no colour blind people took part in the experiment.

Each candidate was given a questionnaire and was shown 8 groups of pictures, each composed of the 6 reproductions obtained by converting the images with the 6 methods previously described. The candidates were asked to rate all the six reproductions of each image using a value between 1.0 and 5.0. The scale was chosen to be simple and intuitive, offering the possibility of using decimals to point out where only minimal differences were present in the images.

After collecting the data, the data was normalised because certain candidates used values outside of the range 1 to 5. The data was normalised only if there was at least a single value in the questionnaire outside of the range. The following formulae were used:

$$
\begin{aligned}
&n = r && ;1 \le R \le 5 \\
&n = 1 + \frac{(r - \min(R))(5-1)}{\max(R) - \min(R)} && ;R < 1 \cup 5 < R \\
&n = \min(r) + \frac{(r - \min(R))(5 - \min(R))}{\max(R) - \min(R)} && ;R < 1 \\
&n = 1 + \frac{(r - \min(R))(\max(R) - 1)}{\max(R) - \min(R)} && ;5 < R
\end{aligned}
\tag{7}
$$

where n indicates the normalised result, r indicates the result being processed and R indicates all the ratings used by a specific candidate on all images. Using the formulae above, the scale used by the candidates were converted, if necessary, to the {1 – 5} range without changing their meaning.

3.2 Results obtained

The results obtained during the two sessions are consistent with each other. The following plot shows the statistics of all the 34 results obtained on each method combined, where the green points represent the average rating obtained for each method, the red line indicates the median, the edges of the blue box represent the 25th and 75th percentiles and the black edges point out the minimum and maximum ratings obtained from each method.

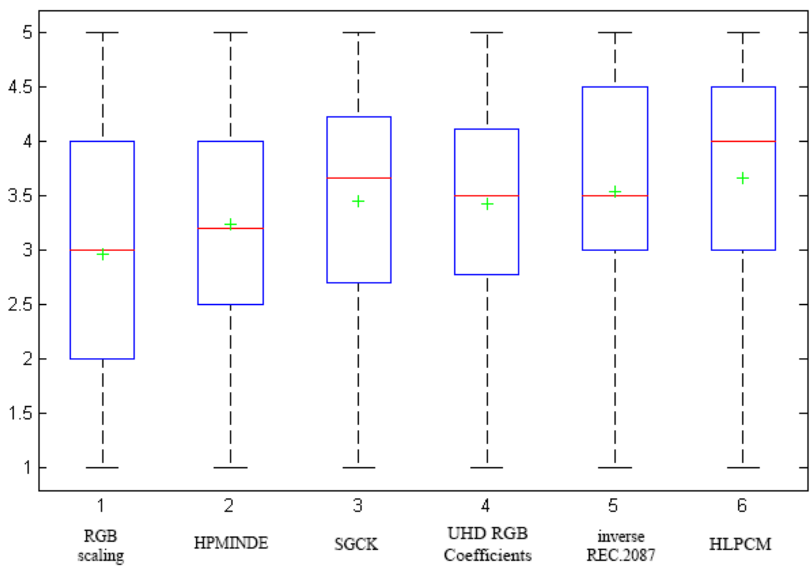

Figure 5 - Box-and-whiskers plot of all the data collected during the experiments.

Since the eight images were all different from each other, the results obtained for each one are slightly different. In the following figure a bar plot is shown containing the average rating for each method on all the different images:

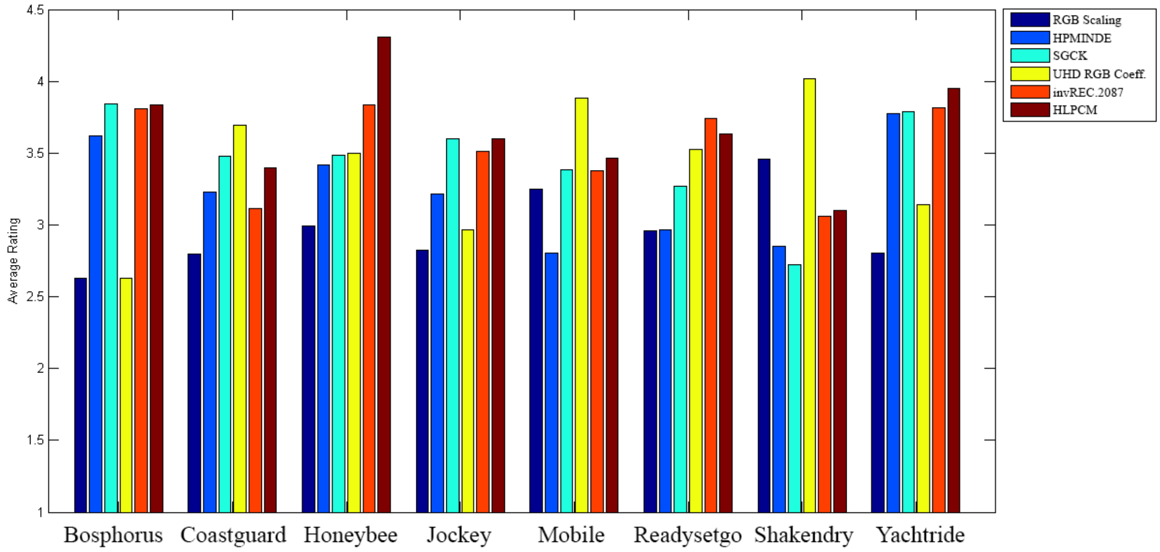

Figure 6 - Bar plot of the average rating of each method for all the images.

4 CONCLUSIONS

To summarise, during this project the following were achieved:

- An extensive literature review that covered the main aspects of colour science, the standards present in the telecommunication field, some basic knowledge on the human vision system, the state of the art GMAs and other established GMAs.
- A series of software tools were programmed to help with the implementation of GMAs and with the analysis of the results.
- Three existing gamut mapping methods were implemented to serve as benchmark for the proposed methods and to have comparable results.
- Three methods were proposed, based on different ideas and built specifically around the conversion from UHD to HD.
- The results obtained on a dataset of 8 images were subjectively evaluated during two sessions by a population of 34 people.
- The ratings obtained during the evaluation sessions were finally analysed to draw definite conclusions on the algorithms implemented.

The objectives set at the start of the project were all met. Furthermore, by analysing the results obtained, it was found that the main of the proposed methods (HLPCM) was the one with the best ratings overall, thus showing the most visually pleasing quality among all implemented methods.

This project's merit lies especially in providing some numerical results on the performance of the different methods, offering a first look at the algorithms which might be used in the future when UHD content becomes available to everyone.

REFERENCES

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APPENDIX I – DATASET[1]

a) Bosphorus

b) Coastguard

c) Honeybee

d) Jockey

e) Mobile

f) Readysetgo

g) Shakendry

h) Yachtride

[1] Sourced from the Ultra Video Group, Copyright Digiturk.

APPENDIX II – HIGHLIGHTED RESULTS

a) RGB Scaling

b) HPMINDE

c) SGCK

d) UHD RGB Coefficients

e) Inverse REC.2087

f) HLPCM

a) RGB Scaling

b) HPMINDE

c) SGCK

d) UHD RGB Coefficients

e) Inverse REC.2087

f) HLPCM

a) RGB Scaling

b) HPMINDE

c) SGCK

d) UHD RGB Coefficients

e) inverse REC.2087

f) HLPCM