Investigation of the colorimetric characteristics of PDP

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ABSTRACT

This paper describes methods to establish robust characterisation models for a PDP (Plasma Display Panel). In addition, the distinct properties of PDP are compared with the other types of displays. The key point in our characterisation model was that the number of sustain pulses was used as an input colour specification rather than RGB input values. Models based on 3D LUT with tetrahedral interpolation and polynomial regression with more than 8 terms were found to give the best performance.

1. INTRODUCTION

There has been much research into the development of colorimetric characterisation models for LCD and CRT displays. To achieve an accurate colour match between an image displayed on a monitor and on other imaging devices such as printers or data projectors, it is important to perform an accurate monitor characterisation within a colour management system. The majority of previous research work concerned with colour management and monitor characterisation is based on CRT displays. [1~2] However more recently, large flat panel displays, such as LCDs or PDPs, have made a great impact on digital consumer electronics. It is therefore hoped to make an accurate colorimetric characterisation model for a PDP on the basis of its intrinsic physical properties so that engineers can use the model practically for different applications. A PDP is composed of two glass plates with a 100μm gap filled with a rare gas mixture (typically 500 torr, Xe-Ne or Xe-Ne-He) which can be made to emit UV photons to excite phosphors. Each pixel has three (RGB) individual micro-discharge cells. Plasma in each cell of an alternating-current (AC) PDP is generated by dielectric barrier discharge operating in a glow regime. The AC voltage is rectangular with a frequency in the order of 100 kHz and a rise time of about 200-300 ns.[3] Grey scale levels on a PDP are obtained via the modulation of the number of current AC pulses in a discharge cell (sustain pulses). For CRT and LCD, the control of grey scale levels is completely different from that of PDP, i.e. through the modulation of voltage. One unique feature of PDP is that its luminance output varies according to the pattern size displayed, even though RGB input values remain the same. An increase in power consumption is accompanied by an increase in the average level of input video signal, which can be considered as a product of RGB input values and pattern size. To compensate for this, PDPs have an Automatic Power Control (APC) function which adjusts their power consumption in order to meet a certain level of electric power specification. Therefore, the resultant luminance values of displayed colour patches are affected by APC levels that, in turn, are decided by the product of RGB input values and pattern size.

This paper investigates the physical properties that can affect colorimetric characterisation and compares three characterisation methods which describe the relationship between the number of sustain pulses of RGB input values and resultant CIE XYZ. These methods are: 3D LUT, polynomial regression and a two-step characterisation model (including linear interpolation for each RGB channel prior to polynomial regression).

2. METHOD

A 42-inch Samsung SDI high-definition PDP was studied, whose pixel resolution is 1024×768 with an aspect ratio of 16:9 and capable of addressing 512 intensity levels per channel. The colour patches were displayed on the PDP through a computer graphic card equipped with digital visual interface (DVI) output. This allows the PDP’s logic board to receive the digital signal directly from the computer. The internal logic board values were set to its minimum black level, i.e. RGB input values were all zero. Usually, the shape of the monitor’s tone reproduction curve (TRC), which represents the relationship between luminance and RGB input values, resembles a power function (having a 2.2-2.5 exponent for a typical CRT). Because this shape correlates well with human perception, the slope of the low luminance range is much smaller than that at high luminance. PDP intrinsically exhibits different TRC shapes according to the pattern size and does not obey a power-function relationship. Hence, the TRC of a PDP should be modified so that its luminance is to be coded to follow human perception. The intrinsic TRCs of five pattern sizes (1, 15, 30, 60 and 100 % by area) and the modified TRC are shown in Figures 1(a) and (b) before and after the modification of gamma respectively.

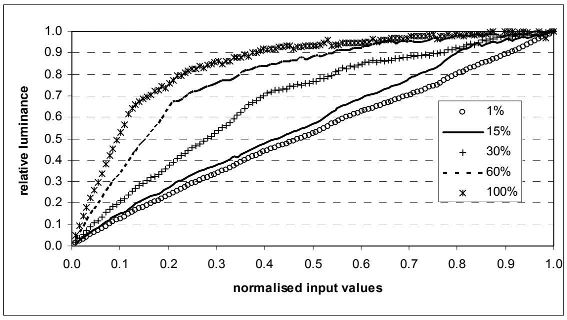

Figure 1(a): Intrinsic TRCs before gamma modification

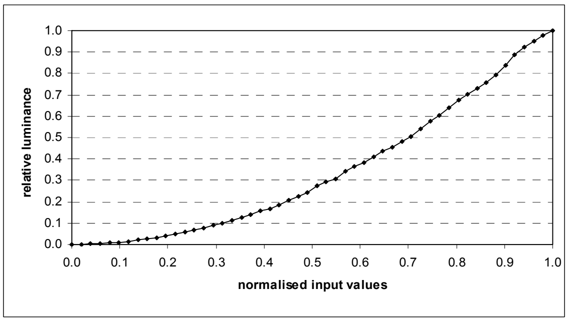

Figure 1(b): TRC after gamma modification

In this paper, three colorimetric characterisation models were made on the basis of the intrinsic TRC so as to make a practical model for a PDP module alone (i.e. without involving a graphic card). Contrary to typical display characterisation, the number of sustain pulses was used as an input colour specification in this study because PDP luminance is proportional to the number of sustain pulses instead of RGB input values. Table 2 illustrates this property that the CIE XYZ values of white colour patches of different pattern sizes having the same RGB input values increase in accordance with an increase in the number of sustain pulses. Measurements were carried out using a Minolta CS-1000 spectroradiometer. All measurements were conducted in a dark room using 100% pattern size.

Table 1: Colour patches for characterisation

Methods / Colour patches	3D LUT	Polynomial Regression	two step model	
			1D LUT	Polynomial Regression
Training set	9-level 3D LUT	9-level 3D LUT	52 steps of RGB	9-level 3D LUT
Testing set	64 test set			

In this study, two training sets were generated. The first set was a 9-level 3D LUT for which the levels corresponded to approximately equal L* intervals. The second set consisted of 52 steps for each RGB channel, thereby constituting 3×1D LUTs between normalised RGB luminance values and the number of RGB sustain pulses. The performance of the three models was tested by measuring 4×4×4 colour patches chosen by {18,83,168,253}. Hereafter, we will name these colour patches '64 test set'. The colour difference (ΔE^*_{ab}) was calculated to evaluate the accuracy of the three models in both forward and reverse directions. All tristimulus values measured were corrected by subtracting those of the black level.

Table 2: Comparison of the number of sustain pulses and CIE XYZ for white colour at different pattern sizes

Pattern size	RGB IVs	APC level	No. of sustain	X	Y	Z
100%	255	255	466	160.1	166.1	185.5
60%	255	219	766	257.2	263.2	305.4
30%	255	146	1376	445.2	443.6	550.2
4%	255	0	2594	873.4	848.0	1135.6

Table 3: Comparison of the number of sustain pulses and luminance for three colour patches at 100% pattern size

Input Values (IVs)			Number of sustain pulses			Luminance
R	G	B	R	G	G	cd/m^2
255	255	255	466	466	466	166.1
255	255	0	700	700	0	221.0
255	0	0	1260	0	0	284.7

3. RESULTS

It is necessary to give an additional explanation so as to why the number of sustain pulses was used as an input colour specification to the PDP characterisation model. Table 2 showed the dependence of the number of sustain pulses on luminance for different pattern sizes of white. The average level of input video signal, a product of RGB input values and pattern size, increases in proportion to an increase in pattern size, accompanied by an increase in power consumption. If a PDP does not have an APC function, the power consumed for large pattern size exceeds a certain level of electric power specification requested by the PDP. Electric power of a PDP is generally controlled through managing the number of sustain pulses, which could be decided by the APC levels in the PDP's logic board. Therefore higher numbers of sustain pulses should be assigned to smaller colour patches. Consequently, the luminance of the 4% pattern size is the highest among the four pattern sizes for white colour in Table 2. This unique property can also be seen in various colour patches of the same pattern size with different RGB input values (Table 3). The three colour patches have the same pattern size, 100%, but the number of RGB cells turned on is different; all three RGB cells are lit white, all two RG cells are lit yellow and only R cells are lit red. As a result, the real display areas of these three colours correspond to 100%, 66.6% and 33.3% pattern size respectively. Therefore red colour, which could be assigned by higher number of sustain pulses, shows higher luminance than yellow and white colours.

Table 4: Tristimulus additivity in neutral colours

RGB IVs	Y (cd/m^2)	APC level	No. of sustain	X	Y	Z
255	166.1	255	466	15.1%	13.9%	16.4%
30	106.2	13	292	16.1%	14.9%	18.3%
15	58.4	0	152	16.1%	15.1%	18.3%
5	20.4	0	50	16.2%	15.6%	18.0%

The additivity of tristimulus values was evaluated. A white patch of 100% pattern size has 466 sustain pulses and an APC level of 255. Hence the tristimulus values of RGB patches with the same number of sustain pulses were measured to evaluate additivity. A substantial difference between white and R+G+B was observed: the sum of RGB is larger than white. This is because the voltage applied to the RGB cells for a white colour is, in practice, lower than that for the individual RGB primary colours. For white, 1024×768×3 cells were turned on whereas individual RGB cells with the same number of sustain pulses as white were turned on alternately for RGB primary colours, i.e. 1024×768 cells. This difference in the number of RGB cells illuminated leads to a small difference in the voltage applied to RGB cells due to a voltage drop and consequently results in a difference in luminance. Finally, RGB luminance values in the white colour patch are slightly lower than those in the individual RGB colour patch. To counteract this large difference in additivity, several matrix coefficient sets – including RGB channel interaction terms (RG RB GB RGB) and square terms of R^2, G^2 and B^2 – were included in polynomial regression. Also, a 3D LUT model was tried. It included many measured data points which can automatically take into account the additivity failure of a PDP.

Table 5: ΔE^*_{ab} colour differences for 64 test set

Test sets \ Models		3D LUT	Polynomial Regression				Three 1D LUT & Polynomial Regression				
			3×5	3×11	3×20	3×35	Primary matrix†	3×3	3×5	3×8	3×11
64 test set	Median	1.47	4.25	1.81	2.06	1.72	8.61	5.94	4.61	2.38	2.24
	Max	4.90	21.15	7.66	7.97	5.46	17.95	23.96	20.48	7.80	8.00

Note: † The primary matrix was achieved by measuring RGB primary colours.

Table 5 summarises the median and maximum colour differences for the 64 test set using the 9-level 3D LUT in its forward direction. In the two-step model, a 3×8 matrix having RGB interaction terms gave better results than a primary matrix and a 3×3 matrix. This is thought to be due to these terms compensating for additivity failure. The 3×11 matrix including square terms did not give any improvement in comparison with the 3×8 matrix. Figure 2 shows a box-plot of the models' performance in terms of ΔE^*_{ab} distribution. For each model, the median is expressed in the middle line of a box and the 25th and 75th percentiles are shown at the bottom and the top of a box respectively. The line above the box is 1 step (1.5 times difference between 25th and 75th percentile) beyond the 75th percentile. The line below the box is the minimum ΔE^*_{ab}. The prediction of CIE XYZ by 3D LUT was accomplished using tetrahedral interpolation.[4] Among the three models, 3D LUT and polynomial regression with more than 5 terms showed a narrower predictive error distribution with a smaller median of ΔE^*_{ab}.

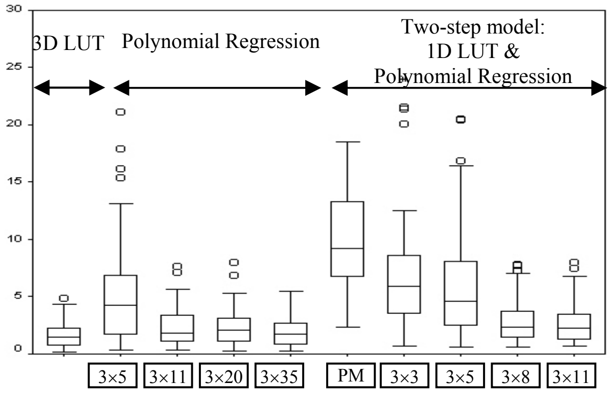

Figure 2: Distribution of ΔE^*_{ab} for 64 test set

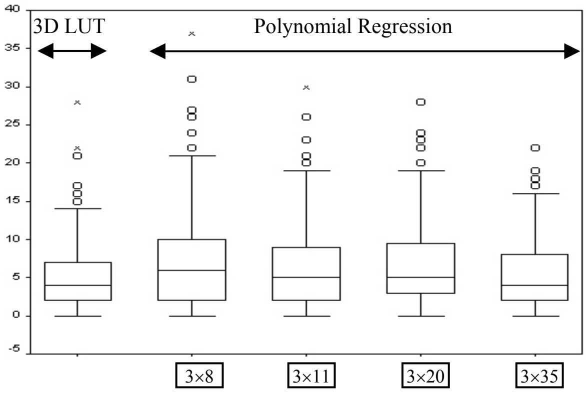

Figure 3: Distribution of the number of sustain pulses predicted for 64 test set

The distribution of the number of sustain pulses predicted by the reverse model is illustrated in Figure 3. The reverse transformation using polynomial regression was made by exchanging the position of input and output data. Those polynomials having more than 8 terms fitted the data well. Again, the ΔE^*_{ab} colour differences were calculated using the predicted number of sustain pulses. The median and maximum of ΔE^*_{ab} for 64-test set are 0.46 and 6.65 for the 3D LUT model with the tetrahedral interpolation. Overall, the 3D LUT model is slightly better than polynomial regression however its weak point is that some colours situated close to the gamut boundary could not be predicted in the reverse direction.

4. CONCLUSIONS

The aim of this study was to introduce the physical properties of a PDP for colorimetric characterisation and to determine an appropriate model for practical application. Three colorimetric characterisation models, which define the relationship between the number of sustain pulses and CIE XYZ values, were successfully derived for a PDP display. A model employing a 3D LUT and another using polynomial regression with more than 8 terms produced more accurate results in both forward and reverse directions. In the near future, these models will be extended to various pattern sizes to make it a more complete characterisation model. In addition, colour and image appearance for a large PDP viewed under practical viewing conditions will be investigated.

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