Two-Field Colour-Sequential Display

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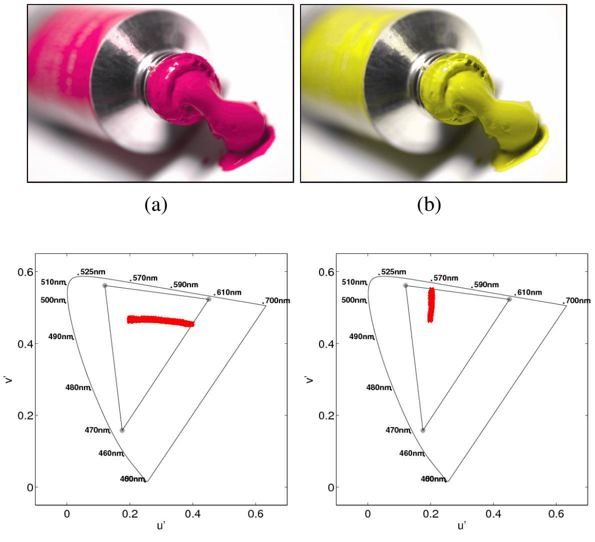
Abstract

Conventional displays use at least three primaries for full colour image reproduction. In this contribution, we discuss the reproduction of colour images using an LC-display system with two local dynamic primaries, based on a segmented backlight. The two primaries are chosen to minimise colour error by means of total least squares. By considering video statistics, it is shown that full colour repreoduction with an accuracy of $\Delta u'v' < 0.02$ for more than 99.9% of the pixels in a segment can be achieved 84% of the time with 2,304 semgments. Simulation results show that two-primary systems can closely resemble colour reproduction of a conventional three-primary system.

Introduction

In order to increase the power efficiency of display systems based on liquid-crystal (LC) panels, the losses due to the colour filters have caught much attention. For example, a colour-sequential display where the colour filters are omitted and replaced by a flashing backlight of red, green, and blue primary colours is a potentially very efficient solution [1, 2, 3]. To avoid annoying flicker, a colour-sequential display requires a panel refresh rate of 180 Hz or higher. The temporal colour synthesis is also the source of the well-known colour breakup effect. These two parameters, the high panel refresh rate and the colour breakup, generally have been perceived as blocking for the commercialisation of colour-sequential displays.



(a) (b)

(c) (d)

Figure 1. *Simple images with magenta-white (a) and yellow-white (b). Below the images, in (c) and(d), the chromaticitiy diagrams of the image pixels are shown in CIE 1976 $u'v'$.*

Recently, advances in video processing has greatly reduced the presence of colour breakup [4, 5]. The proposed concepts are based on an advanced backlight with three primary colours consisting of red, green, and blue light-emitting diodes (LED). The LEDs are segmented and locally addressable. Based on the video content, the primaries are locally adjusted to reduce the colour differences between the primaries, thereby reducing the resulting colour breakup. While a colour-sequential display is several times more power efficient than a regular colour-filter based display, the requirements for fast switching of the LC-panel remains an unsolved problem [2]. As an alternative to a full colour-sequential display operating at 180 Hz and without colour filters, Langendijk *et al.* [6] proposed a hybrid system comprising two wide-band colour filters and two temporal fields. This results in flicker-free operation at a 120 Hz panel refresh rate. The display system is, however, less power efficient than a full colour sequential system. The backlight could consist of two or more light sources, e.g. LEDs, which in combination with the colour filters constitute 4 display primaries, two in each field. These spatio-temporal displays offer an interesting trade-off between power-efficiency and panel refresh rate. Recently, Zhang *et al.* [7] investigated how local dynamic primaries, by means of a backlight with locally addressable LEDs, can reduce colour breakup for spatio-temporal display configurations.

In this paper, we propose a two-field colour-sequential display without colour filters that can operate at a refresh rate of only 120 Hz. Using a fast-switching LC-panel and a segmented backlight consisting of coloured LEDs, colour reproduction relies on local primaries. While regular displays exhibit gamut volumes allowing correct colour reproduction, the two-field scheme reduces the (local) gamut to a plane in a linear colour space. Yet, in this paper we show that two-field colour-sequential displays can have good colour reproduction.

In the following section, we review related work on two-field colour sequential displays. We then introduce the concept of optimal primaries for a local two-primary system followed by simulation results for both simple and natural images. Finally, good colour reproduction of a local two-primary display system is statistically investigated for a large set of video frames followed by discission and conclusions.

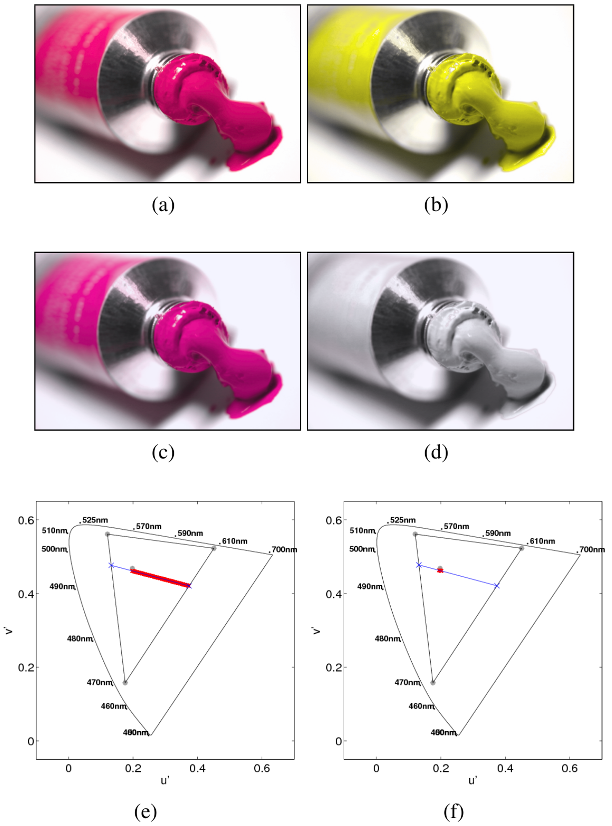

(a) (b) (c) (d) (e) (f)

Figure 2. *Simulated output of (a) and (b) is shown in (c) and (d), respectively. The method applied corresponds to Cheng* et al. *[8]. In (e) and (f) the corresponding output chromaticity is shown in a chromaticity diagram.*

Related Work

It was initially Cheng *et al.* [8] who proposed a two-field colour-sequential display without colour filters in order to combine 120 Hz refresh rate with high power efficiency. Their system combines an LC-panel without colour filters with a locally addressable red, green, and blue backlight. This allow them to create a colourful image with only two local primaries.

In essence, they propose to independently calculate a red and a green field. The blue colour is mixed into these two fields, as "[...] *the human visual system is less sensitive to blue information* [...]", they reason. To show the working principles of this concept, we have included two images shown in Figure 1(a) (magenta-white) and Figure 1(b) (yellow-white). Below the images are the chromaticity diagrams of the pixels in CIE 1976 $u'v'$. The triangle in the chromaticity diagram indicates the colour gamut of the display backlight, in this paper assumed to be ITU Rec. 709 colour primaries. We assume an ideal display without backlight segmentation for this example. The images have been processed using the concept described by Cheng *et al.* [8] applied to a global-addressable backlight and the result is shown in Figure 2(c) and Figure 2(d), respectively.

Notice how the magenta-white image has been (almost) correctly represented with primaries located on the chromaticity lines red-blue and green-blue. For the yellow-white image, however, the colour has not been reproduced at all. As the local primaries are forced to lie on the red-blue (field 1) and green-blue (field 2) chromaticity lines of the gamut triangle, the yellow-white image cannot be reproduced and the image appears black and white.

Obviously the poor colour reproduction for the yellow-white image is not inherent to the display system. In the following section we introduce a method for determining optimal primaries for a two-primary system by explicitly minimising the colour error.

Methods

Good colour reproduction of a two-field colour-sequential display requires optimal choice of the local primaries. We have taken the approach of reducing colour error in terms of chromaticity coordinates. In specific we intend to minimise $\Delta u'v'$ for each set of local primaries. We propose to choose optimal primaries for field 1 and field 2 based on total least squares applied to the chromaticity points of the in input expressed in the CIE 1979 $u'v'$ chromaticity space. For a line $\mathscr{L}: au' + bv' + c = 0$ with slope $-a/b$ and constant $-c/b$, the total least squares is the solution to the problem

$$\underset{a,b,c}{\operatorname{argmin}} \sum_{i=0}^{N-1} \|au'_i + bv'_i + c\|^2 , \tag{1}$$

of the N pixels with chromaticity (u'_i, v'_i) and where we choose $\sqrt{a^2+b^2} = 1$. In fact, the optimal primaries need not be located on the gamut boundary, i.e. along the edges of the colour gamut triangle. Rather the primaries can be represented by the shortest possible line segment given by $\mathscr{L}$ which sufficiently reproduces the chromaticity points in the data set. The advantage of reducing the length of the line is that the primaries will be located closer together and thus reduce visible colour breakup.

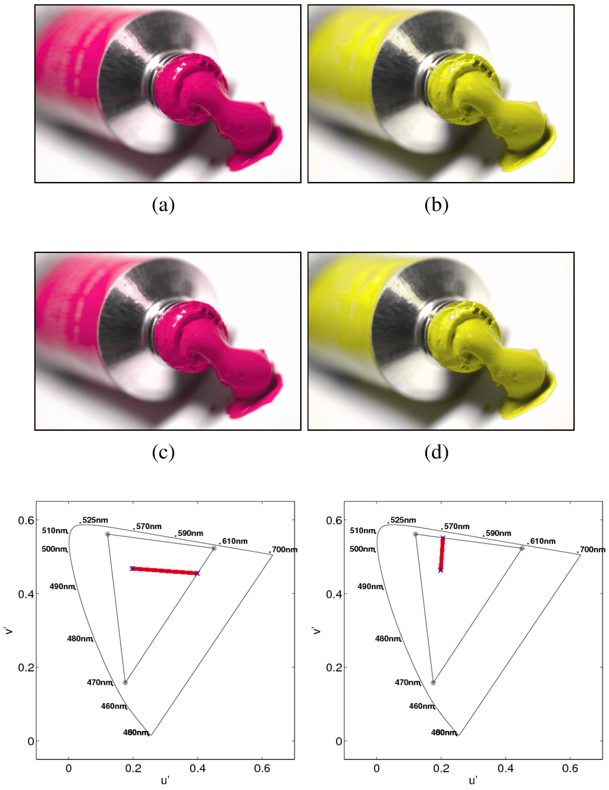
Results

Simple Images

For the image of Figure 3(a) we have computed the optimal primaries using Eq. (1) for a system with a global-addressable backlight. The result is depicted in Figure 3(c) and the reproduced chromaticity in Figure 3(e). Notice how the reproduced chromaticity points resembles the original of Figure 1(c). The local primaries have also been desaturated to the shortest possible line segment without introducing clipping. The primaries are represented by blue crosses in Figure 3(e).

Similar, the optimal primaries have been computed for the yellow-white image of Figure 3(b). The resulting image is depicted in Figure 3(d) and the reproduced chromaticity shown in Figure 3(f). Notice how the image appears colourful, unlike the image in Figure 2(d). Also notice the resemblance of the reproduced chromaticity points with the original chromaticity of Figure 1(d).

The sparse chromaticity distribution of the test images, which lends itself for approximate colour reproduction by a chromaticity line, is not common to natural images. However, as it turns out, small segments of images contains smaller, more local chromaticity distributions, which can be approximated by a chromaticity line. In the following we apply the described optimal two-primary method to a system with a locally addressable backlight.



(e) (f)

Figure 3. *Simulated output of images (a) and (b) is shown in (c) and (d), respectively. The two primaries are established by minimsing colour error using total least squares. In (e) and (f) the corresponding output chromaticity is shown.*

Natural Images

To illustrate the performance of the proposed optimal two-primary system, a number of images have been processed. We initially assumed a backlight segmentation of $(y,x) = (9 \times 16)$. Further the segments are characterised by a Gaussian light distribution. The panel is assumed to be ideal in terms of temporal and electrical response, and the backlight primaries correspond to the ITU Rec. 709 colour primaries.

An image with skin tones, shown in Figure 4(a), is used as input. The simulated output, shown in Figure 4(c), corresponds very well to the input in terms of colour. The input image is seen to be dominated by desaturated colours. The backlight light distribution of field 1 and field 2 is shown in Figure 4(b) and Figure 4(e), respectively. It can be seen to consist of red, white, and cyan.

The difference between the input and the reproduced image is shown in Figure 4(d) and is expressed in $\Delta u'v'$. The colour error is seen to be low. The largest colour error around 0.040 appears in the eyes of the females. This is mainly due to a greenish tinted eye colour. If watched without reference image, the output image seems correct. The error in the hair of the left female is due to the low intensity not perceivable. The results in terms of colour error indicate that this type of natural image is suitable to be reproduced with already 144 segments.

In Figure 5(e) a different input image is shown. The image contains many saturated colours and sharp colour edges. This represents a very critical image to be reproduced by two local primaries. The simulated output, assuming 9×16 backlight segments, is shown in Figure 5(b) and the backlight of field 1 and field 2 is shown in Figure 5(a) and Figure 5(d), respectively. The output image generally resembles the colour impression of the original. However, the colour error is seen to be very large for this image, shown in Figure 5(c). Some image regions even have errors larger than 0.1 in $\Delta u'v'$.

In the colour error map, three regions have been highlighted and marked (1), (2) and (3). These regions mark boundaries between three or more blocks. Due to the restriction of two-primaries, the colour reproduction near these edges can be very poor. For example, for (1) a blue-yellow and a red block are co-located. As the red block is not on the blue-yellow chromatic line, the red colour appears rather yellow close to the boundary of the block. Similar for (2) where a green, red, and white block meet. The backlight primaries are not red, green, or white at this location, but rather yellowish-red and cyanish-green. This gives rise to a colour error for both the red and the green block, while the white block can be reproduced correctly in terms of colour, due to the fact that colour mixing of field 1 and field 2 can yield white.

For region (3), at the intersection of a red, green, and yellow block, the colour error is below the threshold of visibility. The difference with region (1) and (2) is that red, green, and yellow lie on a line in the chromaticity space. It can therefore accurately be represented by two primaries, creating yellow as a mixture of the red and the green field.

As it is expected that more backlight segments will lead to a reduction in colour error for a local two-primary display system, we have repeated the simulation for different backlight segmentations. The image of Figure 5(e) has been processed with 144 (16×9), 576 (18×32), and 2,304 (36×64) segments. The results of these simulations are shown in Figure 5. As the granularity of the backlight increases, the colour errors are clearly reduced. The backlight of field 1 and field 2 (second column of Figure 5) also show how the correlation between the backlight colour and the input image increases with more segments. In the colour error map of Figure 5(l) (2,304 segments), colour errors above the visibility threshold are still present. However, these are all located at the edges of the blocks, or in black regions.

The examples above have highlighted how the performance of the proposed two-field mode depends on the image and on the amount of backlight segments. In the following section, we report a statistical experiment to investigate the relationship between the number of backlight segments and colour error across a large video data set.

Statistical Justification

The goal of the experiment is to statistically justify a local two-primary system with respect to colour reproduction of natural video data. We do this, by computing the colour error across a large set of video data. Further, the relationship between colour error and backlight segmentation is investigated in order to determine the needed effective backlight colour resolution.

In the following experiment we have intentionally not included any display characteristics, rather we have assumed an ideal temporal display response and an ideal backlight separation,


(a)
(b)
(c)
(d)
(e)

Figure 4. *The input image (a) is described using the concept of optimal primaries and* (9×16) *segments, shown in (c). In (b) and (e) the backlight of field 1 and field 2 is shown. The resulting colour error map in* $\Delta u'v'$ *is shown in (d).*

i.e. light distribution are square, non-overlapping blocks. This allows us to evaluate the amount of needed segments in the context of the video source. Of course for a realistic system with certain amounts of light cross-talk between the backlight segments, the results will be worse.

The starting point of the experiment is a video data set collected for IEC 62087 [9] and originally intended to investigate the power consumption of domestic video equipment. The video data is a collection ranging from news to cartoons, scenery to action movie. The sequence contains 17,988 frames corresponding to approx. 10 minutes of video. The duration of the scenes in the collection varies from 30 to 40 frames.

Table 1: Backlight segmentation in the experiment.

Case	# Segs.	Vert. (y)	Horz. (x)	Disp. Cov.
1	1	1	1	100%
2	28	4	7	3.6%
3	144	9	16	0.7%
4	576	18	32	0.17%
5	2,304	36	64	0.04%
6	9,216	72	128	0.01%

The experiment was carried out as follows: 1) each frame was divided into a number of fixed segments; 2) using total least squares, the chromaticity of the pixels for each segment was approximated by a line; 3) the colour error, expressed in $\Delta u'v'$, was computed for each segment. As a result, the per-pixel colour error for all frames and all segments is obtained. To reduce the data set, we counted the amount of pixels within a segment with a colour error $\Delta u'v' > \mathscr{E}$, where $\mathscr{E}$ is a colour-error visibility threshold.

For pixels with $\max(R,G,B) < 4$ (gamma domain), the colour error was reduced by means of a weighing function. Black was excluded from the colour error computation.

The experiment was repeated for a backlight segmentation (y,x) of (1×1), (4×7), (9×16), (18×32), (36×64), and (72×128). The six different segmentations are summarised in Table 1. The vertical and horizontal division is tabulated together with the total number of segments. The display coverage per segment is shown in the right-most column.

The results of the experiment are summarised using a percentile plot in Figure 6. We have set a visibility threshold of $\Delta u'v' > 0.005$. On the vertical axis, the relative number of pixels with a colour error above the visibility threshold within a segment.

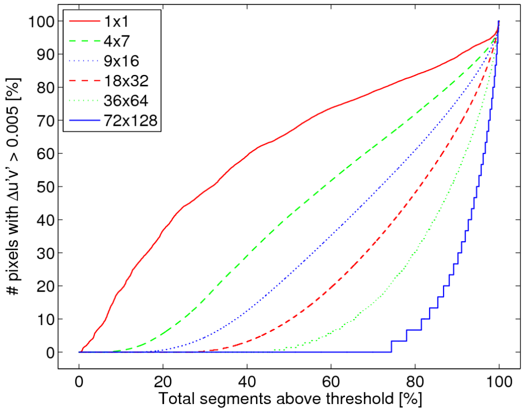
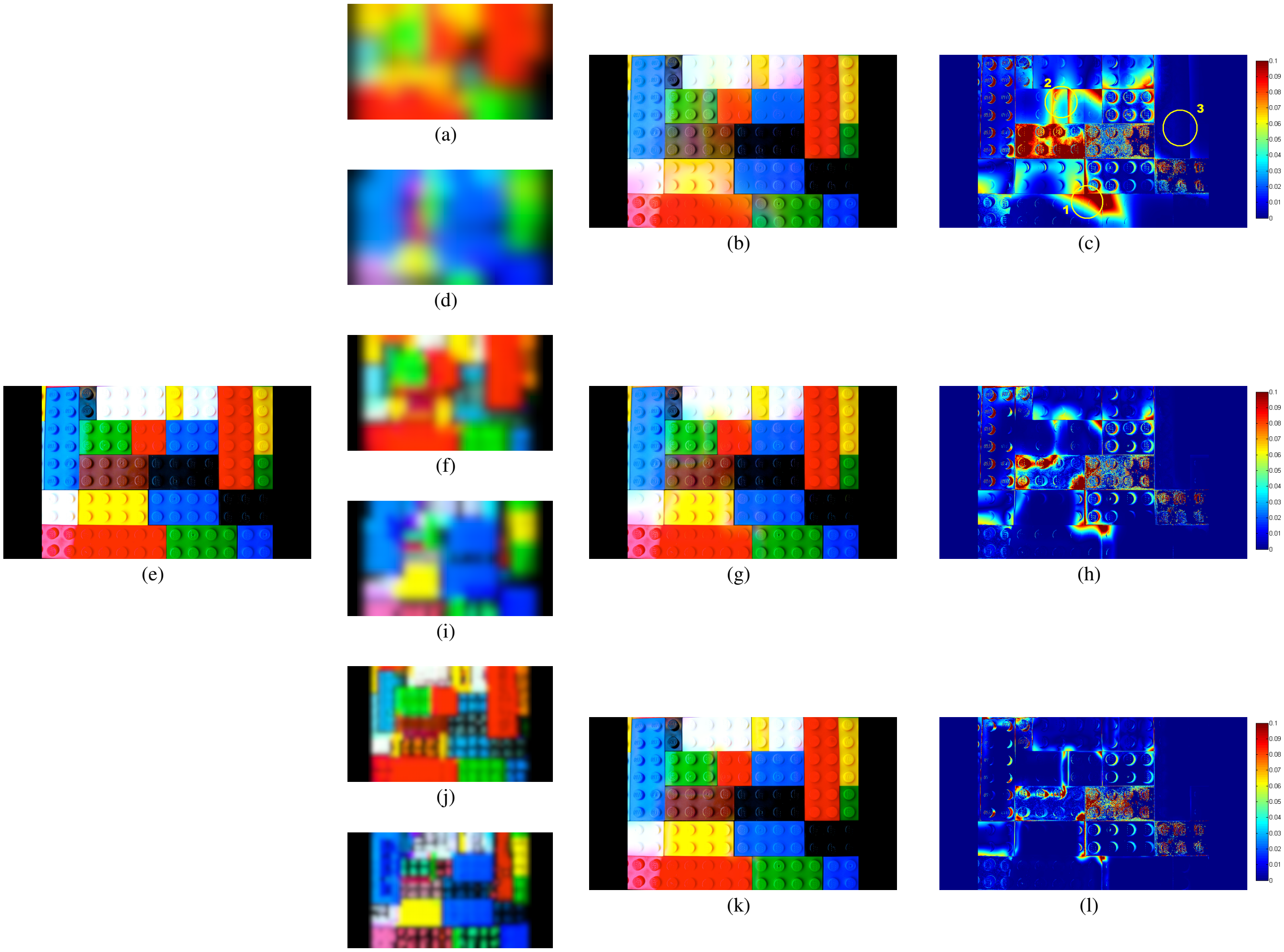


Figure 6. *Results from statistical experiment on IEC 62087 video sequence. On the vertical axis, the number of pixels per segment with a colour error* $\Delta u'v' > 0.005$*. The horizontal axis shows all segments sorted on the number of pixels below the colour error threshold ranging from low to high.*

If the data can be represented by a two-primary system, only few pixels are above the colour error visibility threshold. With 144 segments (case 1), for example, we have 144 segments per frame and 17,988 frames resulting in $144 \times 17,988$ total number of segments. In Figure 6, the number of pixels within one segment with a colour error above the visibility threshold is shown sorted from low to high.

Ideally, the result would be a flat line at 0%. The faster the line goes to more colour errors per segment, the worse the segmentation is. The results clearly illustrates that more segments is beneficial for reducing colour error. For example, for 2,304 segments (case 5, cyan-dashed line) 46% of the segments can be represented with maximum 0.1% pixels per segment with $\Delta u'v' > 0.005$. Without segmentation (case 1, red-solid line) this is less than 0.5%.

The reasoning behind the backlight segmentation is found in the characteristics of natural scenes. Based on similarity of colour, scenes can be segmented into a finite number of super-pixels or objects [10]. Such a representation is possible considering segments of any size and shape. In this experiment the size, shape, and location of the segments is fixed. When several objects of different colour appear within a segment, colour errors may appear. It is therefore expected that more segments would lead to a reduc-



(a) (b) (c) (d) (e) (f) (g) (h) (i) (j) (k) (l) (m)

Figure 5. Simulation results of processing the input image (e) with 144 segments, (b), 576 segments, (g), and 2,304 segments, (k). In the second column, the backlight of field 1 and 2 is shown. In the fourth column, the colour error maps for the respective backlight divisions are shown.

tion in colour error. This is indeed confirmed by the data shown in Figure 6.

A visibility threshold of $\mathscr{E} = 0.005$ is very stringent for colour images. The experiment has therefore been repeated allowing a larger colour error. The results of the experiment for a visibility threshold of $\Delta u'v' > 0.020$ is shown in Figure 7. For the segmentation of the highest granularity with 9,216 segments (blue-solid line), more than 96% of the segments can be represented with less than 0.1% of the pixels above the colour error visibility threshold. With 2,304 segments (cyan-dashed line) this is reduced to 84%, for 576 segments (red-dashed line) to 68%. For a solution without segments (red-solid line) only 5% of the frames can be represented with less than 0.1% the pixels below the colour error visibility threshold.

Discussion

Obtaining the two optimal local primaries by minimising the chromaticity error in $\Delta u'v'$ could be sub-optimal from a perceptual point of view. First of all because intensity is largely excluded from the optimisation. Secondly because the human perception of colour is more complex than discriminating colours. The proposed method assumes a full-reference comparison. However, one could argue that true-colour reproduction need not be the goal in all display applications. It is important to maintain spatial consistency in terms of colour and intensity. For example, objects of constant colour could be reproduced with constant, although changed, colour. Combining local (varying) colour mapping using image segmentation in combination with the two-primary optimisation might be a solution to this.

We have consistently chosen to report the colour error in $\Delta u'v'$ as this corresponds to the optimisation criteria for determining the local primaries. However, as intensity is a very important aspect of colour perception, it might be useful to re-evaluate the simulation results using a method sensitive to intensity. For example using the method described by Johnson and Fairchild [11], which also further includes the spatial acuity of the human visual system.

Based on the statistical experiment, we conclude that it is in-

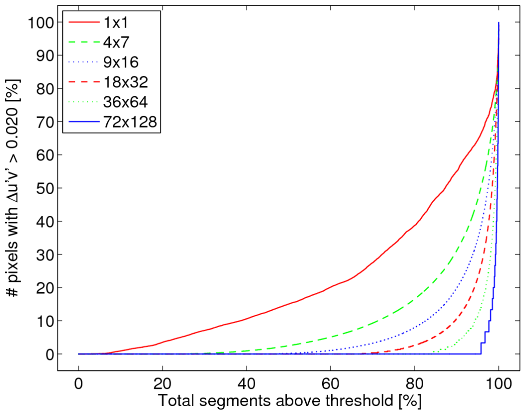


Figure 7. *Results as in Figure 7 but with a colour error threshold of* $\Delta u'v' >$ 0.020.

deed possible to represent data with two local primaries, providing that the backlight is divided in sufficient segments. However, it is worth noting that the light cross-talk between segments will change the local primaries and can therefore reduce the quality of the colour reproduction. If the light distribution of a segment is very local, this reduces cross-talk, however, a wide light distribution might reduce fast colour transitions due to backlight cross-talk. Finally, for a display system, the finite contrast of the LC-panel should be taken into account. In this experiment, we have neglected the fact that the black level is in reality coloured according to the local primaries. The visual effect of a locally varying colour in the black level should not be underestimated.

While it is expected that a two-primary colour-sequential system will suffer less from colour-breakup effects than, for example, a three-primary colour-sequential system, this has to be investigated and validated.

Conclusions

In this paper, we have discussed a local two-primary system operating in colour-sequential mode at 120 Hz field rate. As it uses no colour filters, the system is very power efficient, yet the field rate is lower than for full colour sequential displays with a field rate of 180 Hz or higher. We proposed to chose the two local primaries according to minimum chromaticity error using total least squares.

Natural images are characterised by objects significantly larger than pixels which are of similar colour. By a statistical experiment we have shown that the more backlight segments, the better natural images can be approximated with a local two-primary system. For 2,304 backlight segments a local two-primary system can represent 84% of the segments with less than 0.1% pixels above the threshold of visibility ($\Delta u'v'$ of 0.02). With 9,216 segments this is true for 96% of the segments.

Simulation results of the front-of-screen performance validated the result of the statistical experiment. More segments allow better colour reproduction. Colour reproduction on a two-primary system is not limited to two colours, but rather by the ability to approximate the colours by a chromaticity line.

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