Spectral colour reproduction by vector error diffusion

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Abstract

This paper demonstrates the feasibility of vector error diffusion for spectral colour reproduction using a multi-channel printing device. Using a simplified spectral printer model we demonstrate that spectral vector error diffusion is able to produce a good spectral match, implicitly solves the problem of printer model inversion and achieves reduced visual noise (stochastic moiré) compared to when using standard channel-independent scalar error diffusion.

Introduction

In the context of spectral colour reproduction the goal is typically to reproduce a given target, i.e. a multispectral image, so that the spectral reflectance of every pixel is reproduced as accurately as possible.

To achieve this using inkjet print technology a multi-ink ($N > 4$) system is needed, first to increase the spectral gamut of the device and secondly to allow to find a colorant combination close to the reflectance to reproduce. The limitation on total ink coverage reduces the possibility of spectral reproduction, but a larger choice of colorants can alleviate this problem.

Recently systems with 6 to 8 inks have been proposed for spectral reproduction [1, 2, 3]. In conventional multi-ink colour printing the set of colorants will typically consist of the secondary colours red, green and blue in addition to the conventional primaries CMYK, but for spectral reproduction other primaries might be advantageous [4].

The usual procedure for spectral reproduction involves a printer characterization procedure which establishes a relationship from colorant values to spectral reflectance; the forward printer model. However, it is the inverse relationship which is needed to control the printer device spectrally: a desired spectral reflectance is converted to a colorant combination. The most popular printer model in digital printing is the well known Neugebauer (NG) model and its extension to spectral data. An inversion of the spectral NG model based on iterative method is possible [5] with advantages and disadvantages.

Following these steps two problems among others could occur: the iterative inversion of the model could converge to a sub-optimal solution [6] and some unwanted colours and patterns could appear in the halftoned images [7] due to unwanted interactions between the channels.

After defining the halftoning process and the halftoning techniques such as scalor error diffusion (SED) algorithm we introduce a technique known as vector error diffusion (VED) in the next section. We introduce also our simple printer model and we then describe our experimental setup followed by a discussion of our results, before concluding and providing some ideas for further research in the last section.

Halftoning

Halftoning is needed when the media which is used to reproduce an image cannot reproduce a large number of levels [8]. In the case of digital printing the output pixel can take two different values: ink or not ink. The halftoning process converts a pixel value, typically 8 bits values in the range $[0, 255]$ to a binary level $\{0, 1\}$, indicating whether an ink drop is laid down or not at a particular location. The halftoning could be performed by SED [9].

In SED technique the output pixel value (0 or 1) of an ink channel is calculated independently of the other ink channels. An output pixel is set by a thresholding condition. Then the difference (i.e. the error) between the input pixel value and output pixel value is weigthed by a weight filter and diffused to the neighboring pixels. Several possibilities exist for filter weights, e.g. Floyd-Steinberg [10] and Jarvis-Judice-Ninke [11], aiming to break up the worm patterns typically found in SED. This operation is performed for each colorant channel in a raster scan mode.

The VED technique halftones a picture taking each pixel value of an image as a vector of data [8]. The VED is performed once for the whole image. The threshold condition giving the combination of inks to be printed is calculated as the minimum Euclidean distance in colour space between the desired colour and the primaries colours [7].

The primaries, also called the Neugebauer primaries [12] (NP), are all the possible combinations of the printer colorants at full coverage [4]. The error between the chosen primary and the target colour is then diffused per colour channels to the neighboring pixels identically as in SED algorithm, with a weight filter.

Working with VED has shown improvement regarding the SED drawback of unwanted colours and should increase the quality of conversion reflectance to colorant. However the VED comes also with problems such as error accumulation for colours out of the printer's gamut [13, 14] and slow response to colour changes in the picture.

Comparing to the classic VED our spectral VED chooses the ink's combination minimizing the Euclidian spectral distance between the reflectance to be reproduced and the NP's reflectances. The distance d_k is calculated as in Eq. 1 where $R(\lambda)$ is the target spectral and P_k represents the spectral reflectances of the kth NP.

$$d_k = \sqrt{\sum_{i=1}^{n=31} (R(\lambda_i) - P_k(\lambda_i))^2}. \quad (1)$$

Our spectral data are made of 31 values from $400nm$ to $700nm$ with an interval of $10nm$. Once the P_k is found for the current pixel the error by wavelength between these two reflectances is weighted and diffused by wavelength channels to the neighboring pixels.

Experimental Setup

To evaluate our approach, we generate a testchart of 100 patches. Each patch is made of seven colorants values between $[0,255]$. The patches are created randomly according to the printer's total ink limitation which we set to 300%. We assumed also a stable printer with stable inks and the data we have tested in our testchart were located within the spectral gamut of our printer. The size of a single patch was set to 180×180 pixels so that its halftoned version can be used to control a printer directly.

To simulate the printer device the resulting reflectance of an halftoned patch after SED or VED is estimated with a simple linear model. Assuming a unitary surface for each patch we sum the number of pixel for each primary weighted by the reflectance of the corresponding primary to estimate the reflectance. For example, in a three colorant printing process a pixel after halftoning set to one for two inks on the three available will be weighted by the reflectance of the overlap of these two inks.

Once the teschart was halftoned by SED a spectral testchart was created from these reflectances and the spectral patches are then halftoned by VED. In both SED and VED the error was diffused by the same filter (we used the Jarvis-Judice-Ninke filter). For each patch the resulting reflectance was estimated by our simple linear model.

We used seven inks in our experiments. All the possible combination between the inks were estimated by the Kubelka-Munk model [4]. Following the Neugebauer model a seven ink printer can produce $2^7 = 128$ different combinations. The seven inks were used to estimate all the NP and were printed with the Epson Stylus PHOTO 2100 inkjet printer. Epson photo paper $194g/m^2$ was used and the measurements were taken by the GretagMacbeth Spectrolino/SpectroScan, see Fig. 1 for the reflectances of the seven inks and the paper.

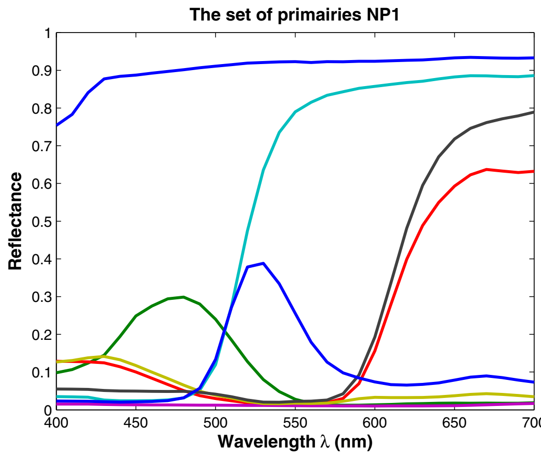

Figure 1. *The spectral reflectances of the paper and the 7 colorants.*

In the spectral VED the distance from the pixel to be halftoned to each NP is calculated and not all are needed. We also run our experiments with less primaries.

We tested the VED for four sets of NP, all including the seven inks and the paper, see Fig. 1. The first set $NP7$ is the full set of NP (total of 128, see Fig. 1, Fig. 2 and Fig. 3). A second set $NP3$ includes all the combinations between the seven inks up to three inks per primaries (total of 64). A third set $NP2$ includes all the combinations between the seven inks up to two inks per primaries (total of 29, see fig. 1 and Fig. 2) and a last set $NP1$ includes only the single inks and the paper, see Fig. 1.

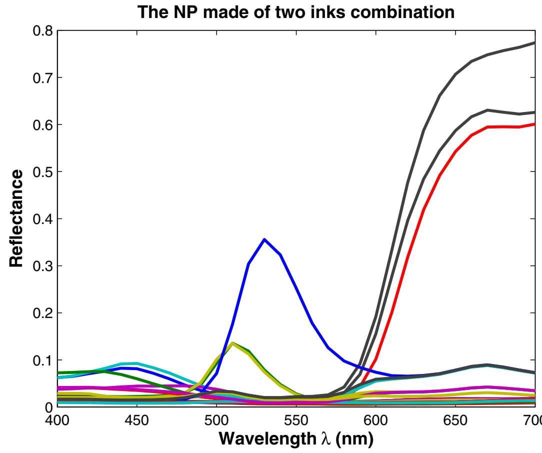

Figure 2. *The spectral reflectances of the NP made of two inks combinations.*

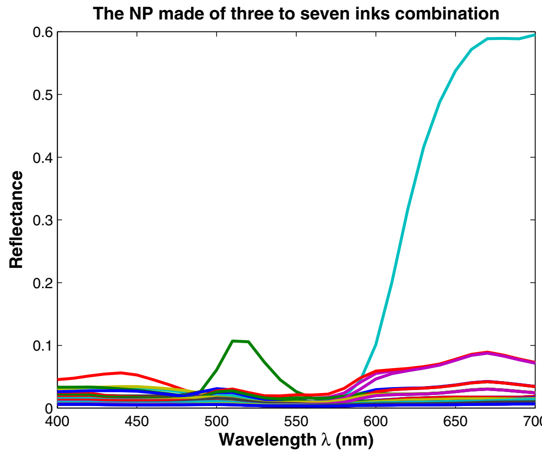

Figure 3. *The spectral reflectances of the NP made of three to seven inks combinations.*

Results and Discussion

In Fig. 4 are represented in sRGB colour space all the patches after SED and VED under illuminant D65. For each patch the sRGB value is calculated from its estimated reflectance. The testchart halftoned by spectral VED and shown in Fig. 4 was performed with the set of primaries $NP7$. The first observation of these two images is that they look quite similar visually.

We compared the sets of estimated reflectances obtained by VED for different sets of NP with the reflectance obtained by SED. For the spectral difference the spectral root mean square RMS (see Eq. 2) was chosen and for the colour difference the ΔE^*_{ab} under the illuminants $D50$, $D65$ and A were calculated to evaluate the reproduction by VED. Table 1 shows the resulting difference for our set of 100 patches, per columns are presented the difference between the patches halftoned by SED and VED for the four sets oF NP starting with the full $NP7$ set to the smallest set $NP1$.

$$E_{RMS} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(R(\lambda_i) - \hat{R}(\lambda_i)\right)^2}. \qquad (2)$$

A closer analysis of the spectral and colour differences shows that not all the NP are needed in the VED. The VED by $NP7$ and the VED by $NP3$ gave the same estimated reflectances and the same spectral and colour differences. These results were obtained without setting any coverage limit on the full set of NP

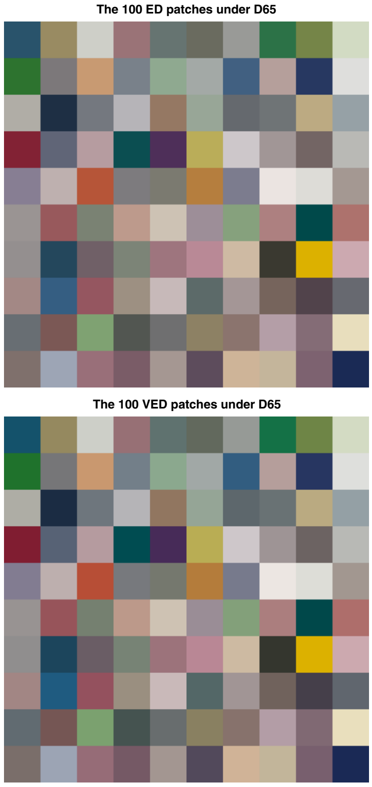

Figure 4. *sRGB renderings under illuminant D65 of the 100 estimated reflectances using SED (above) and VED (below).*

but each pixel of the halftoned images by VED and the $NP7$ set did not use more than three inks.

Table 1: RMS difference and ΔE^*_{ab} difference under illuminants $D50$, $D65$ and A between the patches halftoned by SED and VED for the four sets of primaries.

	$NP7$	$NP3$	$NP2$	$NP1$
	RMS			
Av.	0.0097	0.0097	0.0097	0.0101
Max	0.0136	0.0136	0.0136	0.0136
	$\Delta E^*_{ab}(D50)$			
Av.	1.6635	1.6635	1.6635	1.9031
Max	4.9874	4.9874	4.9874	7.8768
	$\Delta E^*_{ab}(D65)$			
Av.	1.6777	1.6777	1.6779	1.8952
Max	4.7829	4.7829	4.7829	7.4943
	$\Delta E^*_{ab}(A)$			
Av.	1.6594	1.6594	1.6592	1.9553
Max	5.5656	5.5656	5.5656	7.9022

We examined the distributions of the NP on the paper. As example the coloured version of halftoned images of the 1st, 4th, 50th and 87th patch by the SED and VED are shown in Fig. 5, Fig. 7, Fig. 9 and Fig. 11. The patches are arranged columnwise.

The dot distribution of the previous patches can be seen channel by channel in Fig. 6, Fig. 8, Fig. 10 and Fig. 12. For all these examples the VED was performed with the $NP7$ set. From left to right the ink channels, displayed in black and white, correspond to cyan, magenta, yellow, black, blue, red and green colorants.

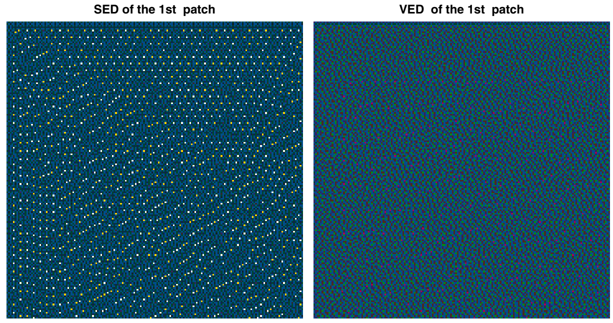

Figure 5. *Coloured HT image under illuminant D50, SED version on the left and VED version on the right.*

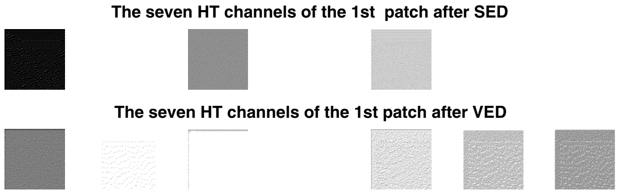

Figure 6. *The seven inks channels after VED. A pixel black means the pixel is on, white is off.*

In color view of the patches, the distribution of the primaries appears less noisy in VED than in SED and this for a small *RMS*. You can see the estimated reflectances curves of the corresponding patches in Fig. 13.

Conclusion and Perspectives

A spectral reproduction system based on Vector Error Diffusion and seven colorants was proposed. Our computational approach gives promising results: the reflectance is directly converted to a dot distribution and is ready to be printed (in theory, because we have assumed a perfect printer) and is close to the initial reflectance.

Moreover, this method is an alternative to the classic spectral printing which requires a forward printer model, the inverse

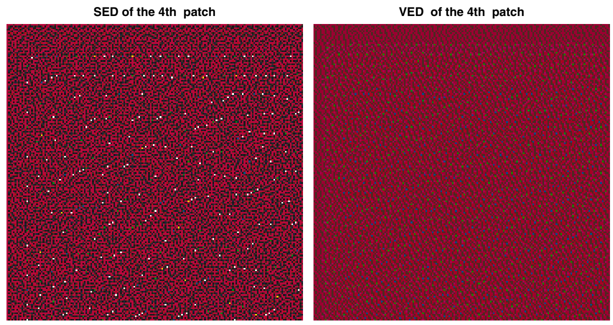

Figure 7. *Coloured HT image under illuminant D50, SED version on the left and VED version on the right.*

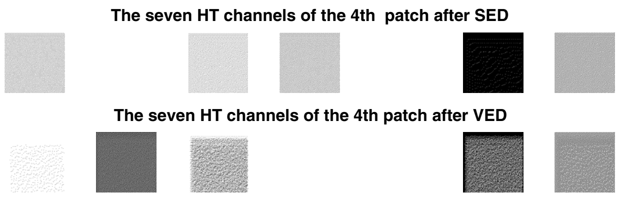

Figure 8. *The seven inks channels after VED. A pixel black means the pixel is on, white is off.*

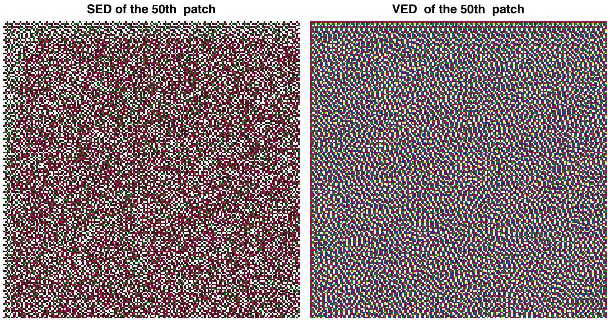

Figure 9. *Coloured HT image under illuminant D50, SED version on the left and VED version on the right.*

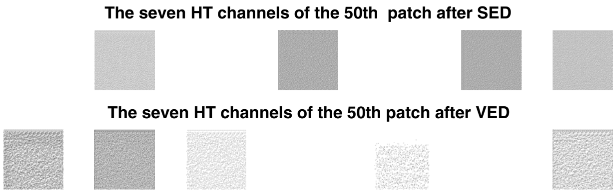

Figure 10. *The seven inks channels after VED. A pixel black means the pixel is on, white is off.*

model, and then the halftoning process. In our experiments the target is directly converted in a dot distribution to be printed.

The spectral VED is a time consuming process and further work should be done to increase the performance of the algorithm. The figures (see Fig. 6, Fig. 8, Fig. 10 and Fig. 12) showing the dots distribution allow to observe the error moving in the colorant channels at the same time in VED and the decreasing of unwanted colour appearances. But it also illustrates the slowness of VED and the accumulation of the error in the process.

A study of the error accumulation, of the primaries interaction and the spectral gamut of the printer should bring improvement and allow to deal with data outside of the printer gamut [15].

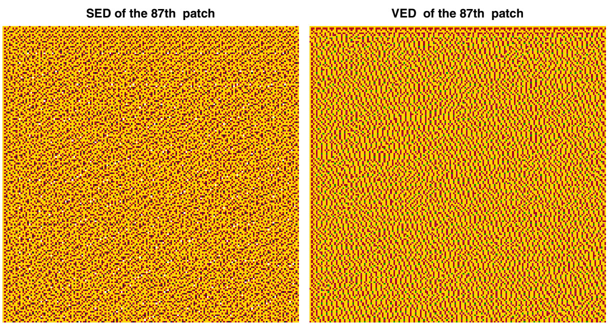

Figure 11. *Coloured HT image under illuminant D50, SED version on the left and VED version on the rigth.*

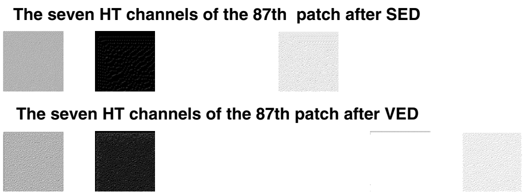

Figure 12. *The seven inks channels after VED. A pixel black means the pixel is on, white is off.*

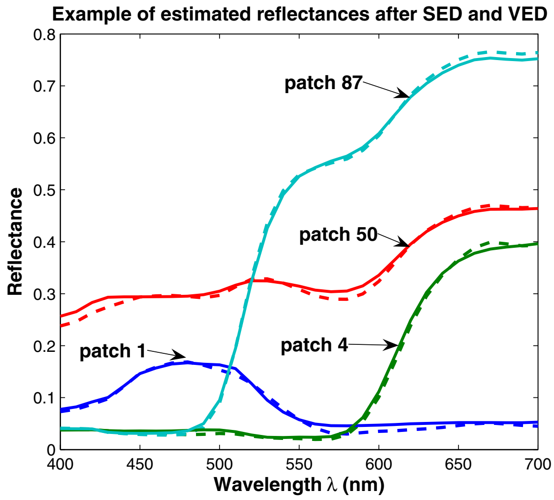

Figure 13. *Estimated reflectance of the previous patches examples. The full lines are the relfectances from the patches after SED and the dashed lines for the patches after VED.*

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