INK LIMITATION
FOR SPECTRAL OR COLOR CONSTANT PRINTING

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ABSTRACT

Ink limitation in the fields of spectral and color constant printing is investigated. In general, a large number of colorants is needed for both applications in order to ensure the required spectral variability. As a consequence ink limitation is required to avoid artefacts such as ink bleeding or bronzing caused by exceeding the maximum total ink coverage of the paper. Simultaneously both applications require a complex separation process where a printer model needs to be inverted subject to the physically printable colorant amounts. The ink limitation workflow proposed in this paper allows for simple constraints that describe the physically printable colorants and can be utilized by spectral or color constant separation algorithms. Experimental results demonstrate that the widely used Cellular Yule-Nielsen spectral Neugebauer model can be used within the ink limitation workflow with an accuracy suitable for spectral and color constant printing.

Keywords: Ink Limitation, Spectral Printing, Color Constant Printing

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INTRODUCTION

The objective of spectral printing is the reproduction of given reflectances so that the match of print and original is invariant to observer and illuminant changes. This is in contrast to common metameric reproductions (e.g. International Color Consortium[1]) that adjust the match of print and original for a specific observer and illuminant utilizing illuminant and observer metamerism. Application areas for spectral printing are for instance artwork reproduction, press proofing or industrial color communication.

The objective of color constant printing is the match of print and original under one specific illuminant and color constancy of the print under other illuminants.

Both objectives have one thing in common: They require a high degree of spectral variability and therefore printing systems with many more colorants than the usual CMYK inks. Systems with 7 (e.g. CMYKRGB) or more colorants allow for a large spectral gamut (the set of all reflectances printable by the system) from which the separation has to chose one specific reflectance. Unfortunately, the large number of colorants causes various problems in printer model

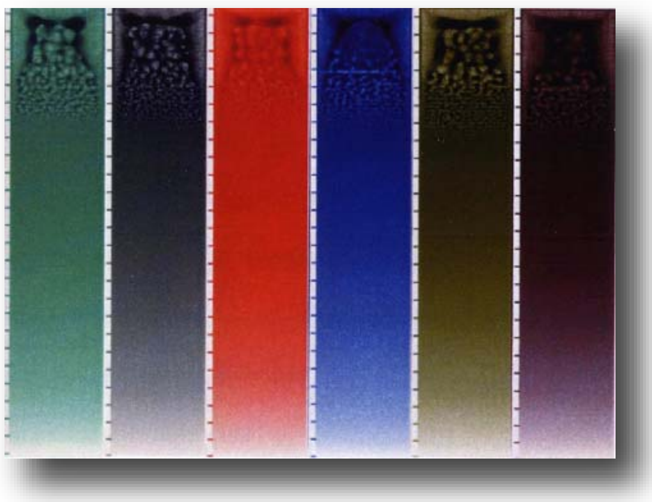

Figure 1: Artefacts caused by exceeding the maximum ink coverage of the paper. The image is extracted from Chen[2]

adjustments and separation:

1. Much more test patches need to be printed in order to reach the required model accuracy.
2. The separation algorithm needs to minimize a specific objective function that utilizes the printer model subject to the ink limit. This constraint is especially important in order to avoid artefacts such as ink bleeding or bronzing caused by exceeding the maximum ink coverage of the paper (see Figure 1. for an example).

An example of such constraint optimization task in case of spectral separation for an m colorant printer is

$$\textbf{minimize} \quad \|R(\psi) - r\|_2$$
$$\textbf{subject to} \quad \psi \in \left\{ \vartheta \in [0,1]^m \,\middle|\, \|\vartheta\|_1 \le \psi_{\max} \right\} = \Omega_{\text{Printable}}$$

where $R(\psi)$ is the printer model, r is the given reflectance, ψ is the vector of colorants (e.g. ψ = (C,M,Y,K,R,G,B)) normalized for each component to one and $\psi_{\max}$ is the maximum area coverage. The printable area used in the constraints is shown in Figure 2 (left). Sometimes the 1-norm (i.e. $\|x\|_1 = \sum_i |x_i|$) utilized in the constraint is replaced by the 2-norm (i.e. $\|x\|_2 = \sum_i x_i^2$). In this case the printable area is shown in Figure 2 (right).

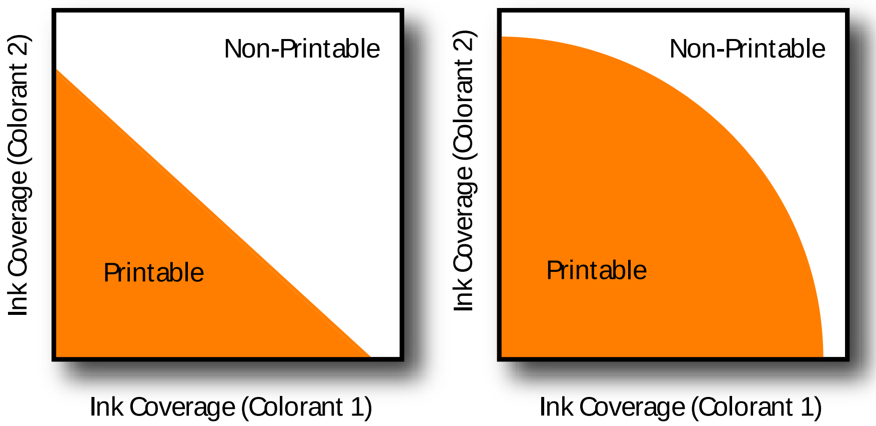

Figure 2: Printable areas within the colorant cube. Left: 1-norm-based printable area. Right: 2-norm-based printable area

Such constrained optimization method needs to be extremely fast in order to be processed for each pixel of a high resolution image. A big problem is parameterizing the constraints. Many different approaches have been investigated reaching from standard constrained optimization methods (e.g. active set methods) to incorporating the constraints into the printer model[3].

In this paper a simple method is proposed that separates the ink limitation from the optimization task. The ink limitation is calculated using multi-linear interpolation of the maximum printable Neugebauer primary control values.

INK LIMITATION

The Workflow

Ink limitation is treated as part of the printer so that the separation algorithm can utilize the whole colorant cube. For this reason the printer control values of the characterization target are first processed by the ink limitation method and subsequently printed as shown in Figure 3.

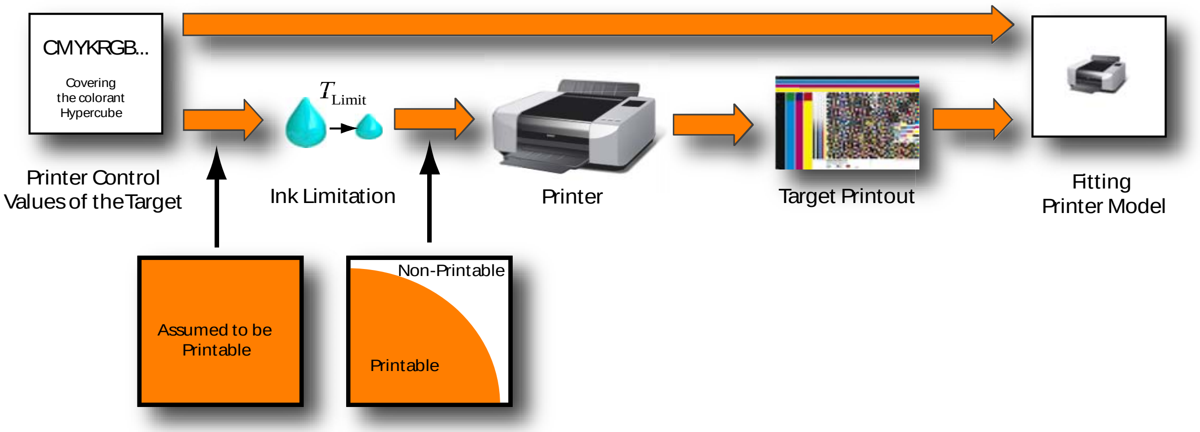

Figure 3: Ink limitation is performed before the target data is send to the printer. The printer model is fitted to the target printout and the non-ink limited control values.

From the perspective of the printer model the whole colorant hypercube is printable. The complex ink limitation constraint used for separation can be replaced by a very simple one. The optimization problem shown above is simplified to:

$$\textbf{minimize } \left\| R(\psi) - r \right\|_2$$

$$\textbf{subject to } \psi \in [0,1]^m = \Omega_{\text{Hypercube}}$$

For solving this constrained optimization problem utilizing the Cellular Yule-Nielsen spectral Neugebauer (CYNSN) printer model a fast method has been proposed already[4,5].

The workflow to print an image is shown in Figure 4.

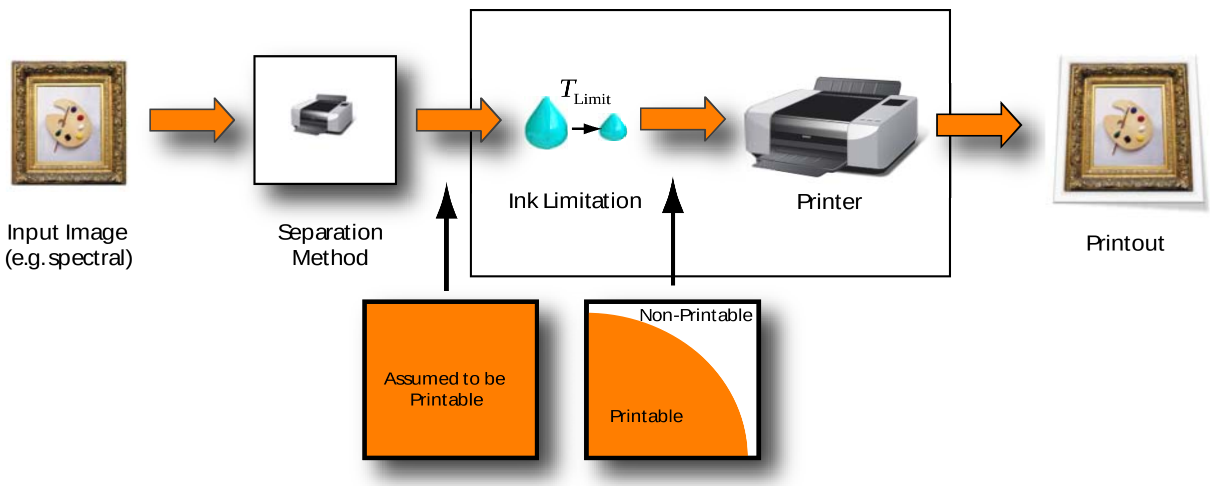

Figure 4: General printing workflow: Ink limitation is treated by the separation method as part of the printer.

Determining the (effective) Maximum Total Ink Coverage

In this paper ink coverage is normalized to one, i.e. 1 ~100%. For a m colorant printer the theoretical maximum ink coverage is therefore m ~ m x100%. In a first step the effective maximum total ink coverage $\psi_{\max}$ for a specific printing system (printer, inks and paper) needs to be determined. For some printing systems this value is specified by the vendor of paper or the Raster Image Processor (RIP). If this information is not available it is necessary to print some test colors with variable ink amount. These colors could be for instance gradients corresponding with Neugebauer primaries. The control values for such a gradient are lying on a line connecting the white point with the Neugebauer primary. For a printing system with m colorants 2^m-1 gradients need to be printed. Figure 1 shows an example for secondary and tertiary colors. The maximum total ink coverage can be determined visually or by spectrophotometric measurements.

Multilinear Transformation for Ink Limitation:

If the maximum total ink coverage $\psi_{\max}$ is known we can transform all colorants within the colorant hypercube $\Omega_{\text{Hypercube}} = [0,1]^m$ into the printable area $\Omega_{\text{Printable}} \subset \Omega_{\text{Hypercube}}$ by using a simple multi-linear interpolation of the (if necessary reduced) control values of the Neugebauer primaries as shown in the following formula:

$$T_{\text{Limit}} = \begin{cases} \Omega_{\text{Hypercube}} \to \Omega_{\text{Printable}} \\ \psi \to \sum_{i=0}^{2^m-1} a_i(\psi) \dfrac{\min(\psi_{\max}, \|g(i)\|_1)}{\|g(i)\|_1} g(i) \end{cases}$$

where

- $g(i)$, $i \in \{0, \ldots, 2^m - 1\}$ is a function that transforms the number i into a vector containing the binary representation of i as components, i.e.

  $g\left(i = \sum_{j=0}^{m-1} x_j 2^j\right) = (x_0, \ldots., x_{m-1})^T$, and $x_j \in \{0,1\}$
- $a_i(\psi)$ are the Demichel formulas. For a CMY printer these are

a_0(C,M,Y) = (1 -C)(1-M)(1-Y)
a_1(C,M,Y) = C(1-M)(1 -Y)
a_2(C,M,Y) = (1-C)M(1-Y)
a_3(C,M,Y) = (1-C)(1-M)Y
a_4(C,M,Y) = (1-C)MY
a_5(C,M,Y) = C(1-M)Y
a_6(C,M,Y) = CM(1-Y)
a_7(C,M,Y) = CMY

The function $g(i)$ defines the control values of the Neugebauer primaries. The fraction $\frac{\min(\psi_{\max}, \|g(i)\|_1)}{\|g(i)\|_1}$ limits these control values if they exceed the maximum total ink coverage (i.e. $\min(\psi_{\max}, \|g(i)\|_1) = \psi_{\max}$) or leaves them unchanged in case they are printable (i.e. $\min(\psi_{\max}, \|g(i)\|_1) = \|g(i)\|_1$). The Demichel formulas satisfy the conditions $a_i(\psi) \geq 0$ and $\sum_{i=0}^{2^m-1} a_i(\psi) = 1$. The evaluation of T_{Limit} at a position $\psi \in \Omega_{\text{Hypercube}}$ is simply a multi-linear interpolation of the Neugebauer primary control values reduced to become printable. Figure 5 shows an example of the multi-linear transformation for a printer with two colorants. Figure 6 visualizes the corresponding total ink coverage map.

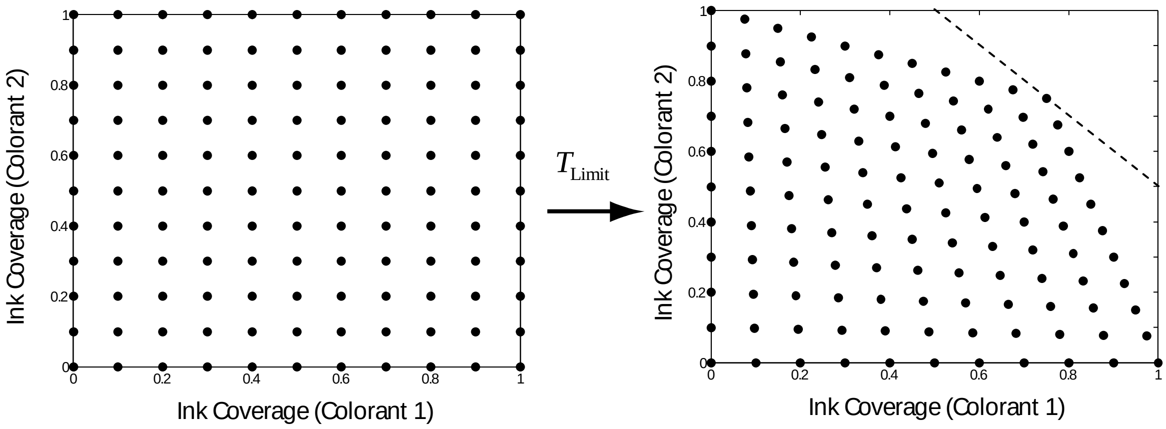

Figure 5: Example of the multi-linear transformation for a printer with two colorants and $\psi_{max}=1.5$.

As can be seen from Figure 5 the resulting printable area does not cover the whole theoretical printable area (bounded by the dashed line). In practical applications this problem does not lead to a significantly smaller gamut if paper is used that allows a maximum total ink coverage larger than 3 (~300%). In these cases (typical for spectral and color constant printing) the Neugebauer primaries that consist of overprints of three colorants are not changed by the transformation. Hence the printable area of all combinations of three overprints is covered, i.e. all combinations of three colorants with a total ink coverage up to 3 can be accessed. Even if the paper allows a higher maximum total ink coverage than 3 adding more ink results in extremely small reflectance factors (very dark colors) that are expected to increase the spectral gamut only marginally.

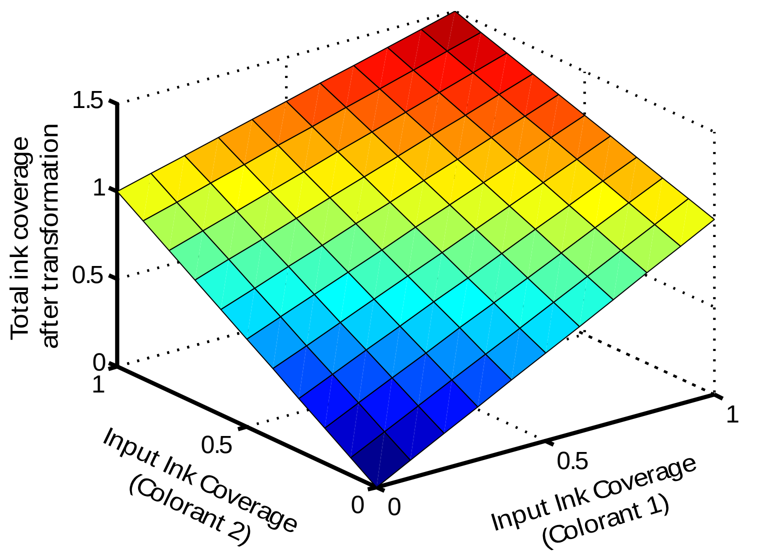

Figure 6: Total ink coverage map after the multi-linear transformation for the example shown in Figure 5

It is possible to construct a transformation that maps the colorant hypercube to the whole theoretical printable area. Such a transformation needs to fulfill some properties such as smoothness of the resulting total ink coverage map. Furthermore the total ink coverage map cannot contain any local minima. Compression methods known from gamut mapping can be utilized to construct such transformations for instance. Further research is required since the objectives differ from the objectives typically used for gamut mapping. On the other hand such gamut-mapping-like methods applied in more than three dimensions are computational expensive and the resulting gain in gamut size compared to the multi-linear transformation is expected to be small. The proposed multi-linear ink limitation method can be seen as a trade-off between computational complexity and spectral gamut size.

APPLICABILITY FOR SPECTRAL AND COLOR CONSTANT PRINTING

In this section the applicability of the ink limitation workflow utilizing the multi-linear transformation shall be investigated for spectral and color constant printing. This can be validated by the accuracy of the printer model that is used by the separation method. It is sufficient to show that by fitting the printer model as shown in Figure 3 its prediction accuracy in terms of spectral and colorimetric errors remains reasonable.

The ink limitation workflow described above was already successfully used by an experimental spectral printing system[6] and also for colorimetric separations[7]. The accuracy of the spectral system utilizing a CMYKRGB printer (HP Designjet Z3100 Photo) for reproducing a painting in the style of Vincent van Gogh's Church at Auvers was described by Berns et al.[8]. Average error rates between CYNSN model prediction and real printout are $\Delta E_{00} \leq 2$ for illuminants D65 and A and the 2° and 10° CIE standard observer.

In this paper the same characterization was performed using the Canon iPF5000 printer instead of the HP Designjet Z3100 Photo printer. The CMYKRGB ink set of the 12-ink printer was used. To characterize the printer a target of 7725 training printer control values was ink limited and then printed. 20 optimized CYNSN sub-models[9] (5 grid points) were adjusted to the target's non-ink limited control values and the corresponding measured printout as shown in Figure 3. To test the printer model 7725 different printer control values were chosen located between nodes of the printer model. These values were used in a first step to calculate a model prediction. In a second step they were ink limited and printed. The printouts were compared with the model prediction.

	Mean	**std**	**95th***	**Max**
RMS	0.0053	0.0033	0.0120	0.028
CIEDE2000, CIEA	0.8361	0.5003	1.7261	4.55
CIEDE2000, CIED50	0.8169	0.4794	1.6591	4.89
CIEDE2000, CIEF11	0.8375	0.5267	1.7283	6.10

* 95th percentile = value below which 95% of observations fall

The results shown in the table are similar to results for the Designjet Z3100 Photo printer mentioned before. More meaningful is their similarity to results obtained by utilizing different ink limitation techniques and workflows [9,10]: Chen et al.[10], for instance, used a CYNSN model with 4 gridpoints to characterize a CMYKOG (O = orange, G = green) printer. He statistically predicted non-printable colors to fit the model to the limited number of (printable) training colors to allow for a regular grid. The mean and maximum RMS prediction errors of six hundred randomly selected colors were 0.008 and 0.045, respectively. The corresponding mean and maximum CIEDE2000 color errors (CIED50, 2° observer) were 0.96 and 3.86. Although Chen uses a 4 gridpoint model, his printing system utilizes fewer inks (six instead of seven) and the test colors were selected randomly (and not between the nodes as in our experiment) the error rates have the same magnitude as the error rates shown in the table.

These results validate that the empirical nature of the CYNSN model allows the usage of the described ink limitation workflow and multi-linear ink limitation method without significant loss of accuracy. In addition to the *n*-value that empirically models the optical dot gain the CYNSN model is based on simple interpolation. Compared to a pure physical model this requires more training colors for the nodes but enables the modeling of a wide variety of printing system including the ink limitation workflow described in this paper.

The advantage of the proposed method is the simplification of constraints for separation. This allows a reduction of complexity and a faster computation[4].

CONCLUSION

In this paper an ink limitation workflow and an ink limitation method is proposed to simplify the ink limitation constraints for spectral and color constant separation. The main idea is to separate the printer model from ink limitation. For this reason the target's printer control values are ink limited and printed and the model is adjusted to the printouts and the non-ink limited target values. As a result the printer model is defined for the whole colorant hypercube that only needs to be considered in the constraints of the separation method. Ink limitation becomes a post-processing step directly before printing.

For ink limitation a transformation was proposed that uses ink reduced control values of the Neugebauer primaries as nodes of a multi-linear interpolation. Experimental results show that this method in combination with the ink limitation workflow is suitable for spectral and color constant printing. The model accuracy of the typically used Cellular Yule-Nielsen Spectral Neugebauer model is not changed significantly compared to other ink limitation methods already successfully utilized for spectral and color constant printing.

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