Model-based design of recto-verso prints displaying different images according to the illuminated face

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Abstract

Predicting simultaneously the spectral reflectance and transmittance of halftone prints is now possible thanks to a recently developed model based flux-transfer matrices, called Duplex Primary Reflectance-Transmittance model, valid for single-face printing as well as duplex printing. The model can be calibrated from either spectral reflectance measurements or spectral transmittance measurements; but it can also be calibrated from both measurements by minimizing the distance between the theoretical transfer matrices and experimental transfer matrices. According to the test carried out with paper printed in inkjet, the predictive performances of DPRT model, coupled with the new calibration method, are good enough to permit interesting applications in graphical arts, such as the display of multiple images depending on whether the light source is in front of the duplex color print or beside it.

Key-words: Computational printing, Duplex halftone prints, Flux transfer matrix, Halftone image reproduction, Spectral reflectance and transmittance.

1. Introduction

After decades of progresses on the predictive performances of spectral reflectance models for halftone prints [1], and the more recent development of spectral transmittance models also applicable to duplex halftone prints, i.e., papers printed on both faces [2-5], it is now possible to predict printable colors with good accuracy and low calibration effort for many printing systems and many kinds of printing supports. It is therefore possible to imagine interesting applications in graphical arts or object designs playing with duplex printing on translucent printing supports, for example displaying different images according to the face that is illuminated. For such applications, a predictive model is decisive for at least two reasons. The first reason is the calibration of the duplex printing system: if it is possible to calibrate a printing system in reflectance mode by measuring hundreds or thousands of printed color patches, the square of this number of patches would be needed in duplex halftone printing for which both spectral reflectance and transmittance must be measured. With a predictive model, the number of needed color patches is reduced to a few tens [5]. The second reason is that in applications where multiples images are targeted according to the illumination conditions, the digital color layouts to be designed for the recto and verso faces need to be computed with precision, especially when patterns visible in one illumination mode must disappear in the other illumination mode by color matching with their surrounding patterns. This necessity of precision, which immediately discards ICC profiles, implies that the predictive model is carefully selected and calibrated, in order to take into account the correspondence between the nominal surface coverages of the inks (CMY values in the digital layouts) and their effective surface coverages once printed.

The classical approach would consist in selecting a reflectance-only model, calibrated from reflectance measurements, for the reflectance predictions, and a transmittance model, calibrated from transmittance measurements, for the transmittance predictions. This approach is the most accurate for predictions in either mode, but the two models, calibrated independently of each other, generally have different nominal-to-effective surface coverage functions [4]. This is an issue for computing the CMY values of the recto and verso layout in order to achieve targeted colors in the different illumination modes, because the different models do not indicate the same nominal ink surface coverages. We therefore recommend a recently developed model based on flux transfer matrices, called Duplex Primary Reflectance-Transmittance (DPRT) model [5], which is calibrated from both reflectance and transmittance measurements and allows simultaneous prediction of the reflectances and transmittances of duplex halftone prints on its two faces. After recalling the mathematical concepts on which the model is based and the way it is calibrated, we propose to analyze its prediction performance and to show one example of multiple-imaging application that we designed by using this model.

2. Background: The two-flux transfer matrix model

The two-flux matrix transfer model presented in [5] applies with a stack of planar optical components such as layers of materials or interfaces between layers. These components are said to be *symmetric* when they have same reflectance (and same transmittance) on their two faces, and non-symmetric otherwise. We characterize them by four *transfer factors*: the *front-side reflectance* r, the *back-side reflectance* r', the *forward transmittance* t and the *backward transmittance* t'. All fluxes and transfer factors may also depend upon wavelength. The mutual exchanges between downward and upward fluxes propagating can be represented by the transfer matrix:

$$\mathbf{M} = \frac{1}{t}\begin{pmatrix} 1 & -r' \\ r & tt' - rr' \end{pmatrix} \quad (1)$$

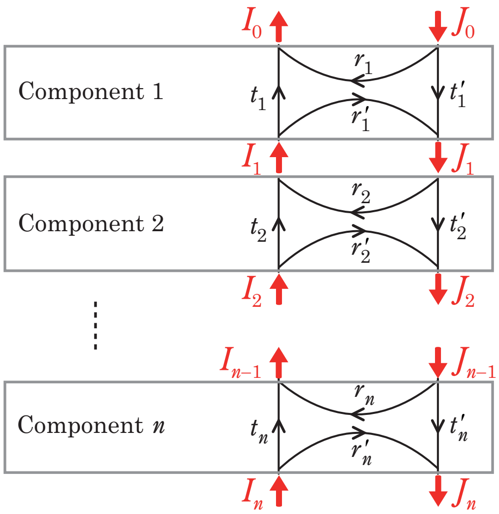

Figure 1: Flux transfer between n diffusing layers.

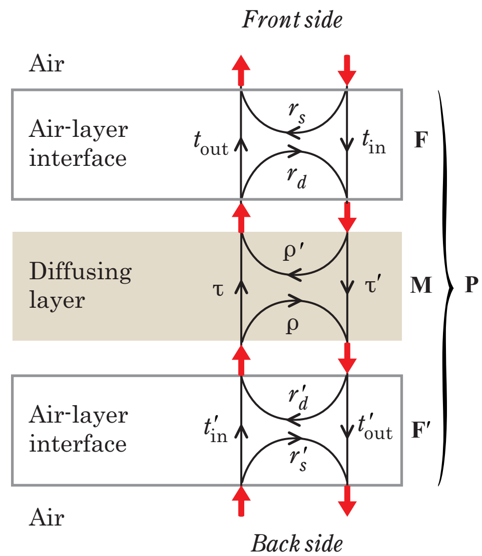

Figure 2: Flux transfers between a diffusing layer bordered by interfaces with air.

One can also show that when two components are on top of each other, the multiple reflections occur between them and the transfer matrix of the stack of these two components is the product of the transfer matrices of the individual components. More generally, Figure 1 shows the stack of n non-symmetric components with transfer matrices $\mathbf{M}_i\left(i=1,\ldots,n\right)$ having the structure displayed in Eq. (1) and with transfer factors r_i, r_i', t_i and t_i'. The stack is equivalent to a non-symmetric component whose transfer matrix is:

$$\mathbf{M} = \mathbf{M}_1 \cdot \mathbf{M}_2 \cdot \ldots \cdot \mathbf{M}_n \equiv \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix} \quad (2)$$

Provided $m_{11} \neq 0$, one retrieves the transfer factors in the following way:

$$\begin{aligned} r &= m_{21} / m_{11} \\ t &= 1 / m_{11} \\ r' &= -m_{12} / m_{11} \\ t' &= \det \mathbf{M} / m_{11} = m_{22} - m_{21} m_{12} / m_{11} \end{aligned} \quad (3)$$

3. Diffusing layer and interface

The individual reflectances and transmittances of the interface derive from the Fresnel formulas and depend on the illumination and observation geometries. They are generically denoted as r_s for the air-side reflectance, r_i for the layer-side reflectance, t_{in} for the air-to-layer transmittance and t_{out} for the layer-to-air transmittance (Figure 2.*a*). Their detailed computation can be found in [4]. For a refractive index of 1.5, typical printing materials, and a hemispherical-directional (d:8°) measuring geometry, the numerical values of these transfer factors are: r_s = 0.04, r_i = 0.60, t_{in} = 0.90 and t_{out} = 0.43. The transfer matrix attached to the air-layer interface is therefore:

$$\mathbf{F} = \frac{1}{t_{in}} \begin{pmatrix} 1 & -r_d \\ r_s & t_{in} t_{out} - r_s r_d \end{pmatrix} = \begin{pmatrix} 1.111 & -0.667 \\ 0.044 & 0.403 \end{pmatrix}. \quad (4)$$

Using similar notations, the matrix for the interface at the back side of the layer (Figure 2.b) is:

$$\mathbf{F}' = \frac{1}{t_{out}'} \begin{pmatrix} 1 & -r_s' \\ r_d' & t_{in}' t_{out}' - r_s' r_d' \end{pmatrix}. \quad (5)$$

In the case of a diffusing printing support, whose two interfaces can be assumed of same relative refractive index, the transfer matrix **P** attached to the support (interfaces included) and the transfer matrix **M** attached to the diffusing layer (interfaces excluded) are related by the matrix equation:

$$\mathbf{P} = \mathbf{F} \cdot \mathbf{M} \cdot \mathbf{F}'. \quad (6)$$

Since the transfer factors contained in matrix **P** can be directly measured and the matrices **F** and **F**’ are known as soon as the support’s refractive index is estimated and the measuring geometry is determined, we can compute the transfer matrix attached to the diffusing layer as:

$$\mathbf{M} = \mathbf{F}^{-1} \cdot \mathbf{P} \cdot \mathbf{F}'^{-1}. \quad (7)$$

4. Duplex primary reflectance-transmittance model

A paper printed with a solid layer of ink is a typical case of nonsymmetrical component. It is classical, after Clapper and Yule, to consider the inked paper as a three-component structure: the diffusing paper background, the ink layer (unable to reflect light by itself) and ink-air interface. We propose here a different approach where the inked paper with interface is considered as one nonsymmetrical component.

The model developed in the previous section for a nonsymmetrical diffusing layer with interfaces can be extended to layers with non-homogeneous surfaces, typically paper substrate coated with halftone ink layers. In the following, we will consider CMY halftones, containing eight Neugebauer primaries respectively labeled from 1 to 8; the value $i=1$ correspond to white (surface with no ink) and the others values correspond respectively to cyan, magenta, yellow, red (magenta and yellow), green (cyan and yellow), blue (cyan and magenta) and black (cyan, magenta and yellow).

For a paper coated on one side with a halftone containing 8 primaries, we subdivide the paper area into 8 sub-areas, corresponding to the different primaries with respective surface coverage a_i (i = 1,..,8) deduced from Demichel's equations [6]. For a paper coated with halftones on its two sides, its area is subdivided into 8 × 8 = 64 sub-areas corresponding to the different combinations of front and back primaries. These 64 *duplex primaries* have transfer factors $\rho_{ij}, \rho'_{ij}, \tau_{ij}$ and τ'_{ij}, and surface coverage $a_i a'_j$ (i = 1,..,8, and j = 1,..,8). Figure 3 shows an example of duplex halftone print with two primaries on each face, therefore four duplex primaries.

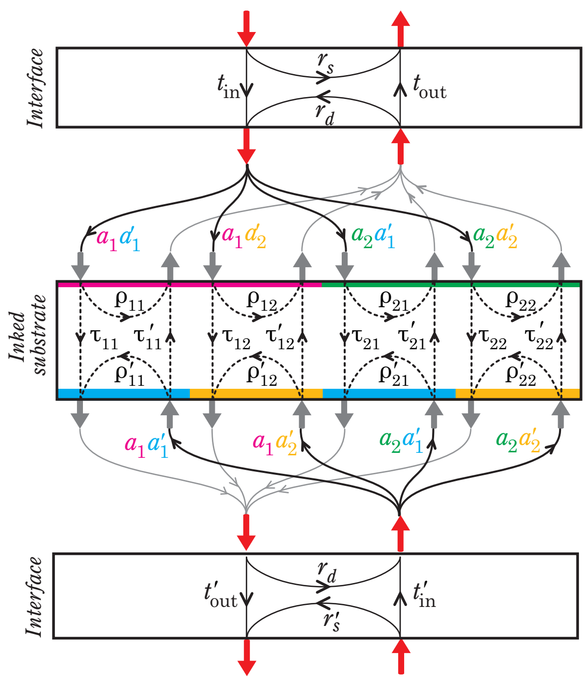

Figure 3: Flux transfers between the front interface, the inked substrate containing four duplex primaries (combination of two primaries on each face) and the back interface.

Hence, the substrate with halftones on its two faces has the transfer factors:

$$\begin{aligned} \rho_H &= \sum_{i,j} a_i a'_j \rho_{ij} \\ \tau_H &= \sum_{i,j} a_i a'_j \tau_{ij}, \\ \rho'_H &= \sum_{i,j} a_i a'_j \rho'_{ij} \\ \tau'_H &= \sum_{i,j} a_i a'_j \tau'_{ij}, \end{aligned} \quad . \tag{8}$$

and the transfer matrix $\mathbf{P}_H$ representing the duplex print with interfaces is given by

$$\mathbf{P}_H = \mathbf{F} \cdot \frac{1}{\tau_H} \begin{pmatrix} 1 & -\rho'_H \\ \rho_H & \tau_H \tau'_H - \rho_H \rho'_H \end{pmatrix} \cdot \mathbf{F}' . \tag{9}$$

The transfer factors R_H, R'_H, T_H and T'_H obtained from (9) by using the formulas (2) are:

$$\begin{aligned} R_H &= r_s + \frac{1}{\Delta} t_{in} t_{out} \left[\rho_H - r_d \left(\rho_H \rho'_H - \tau_H \tau'_H \right) \right] \\ T_H &= \frac{1}{\Delta} t_{in} t'_{out} \tau_H , \\ R'_H &= r'_s + \frac{1}{\Delta} t'_{in} t'_{out} \left[\rho'_H - r_d \left(\rho_H \rho'_H - \tau_H \tau'_H \right) \right], \\ T'_H &= \frac{1}{\Delta} t'_{in} t_{out} \tau'_H , \end{aligned} \tag{10}$$

with $\Delta = (1 - r_d \rho_H)(1 - r_d \rho'_H) - r_d^2 \tau_H \tau'_H$.

5. Calibration and verification of the model

The calibration of the model is made in two steps. The first step is the determination of the spectral transfer factors of each of the 64 duplex primaries. The second step is the ink spreading assessment (mechanical dot gain). It consists in deriving from measured and predicted spectra of single-ink halftone the so-called ink spreading functions which transform nominal surface coverages into effective ones [1]. A detailed description can be found in [5] where three methods to compute ink spreading functions are proposed: 1) minimizing the quadratic difference between the predicted and measured spectral reflectances or transmittances, 2) minimizing the equivalent CIELAB ΔE_{94} color distance between them, and 3) minimizing the "distance" between the transfer matrices created from the measured spectral transfer factors and from the predicted ones. Methods 1 and 2 yield a set of 24 ink spreading functions (12 functions in reflection mode, 12 in transmission mode) and method 3, using simultaneously reflectance and transmittance factors in the transfer matrices, yields one set of 12 ink spreading functions.

In our experiment, we printed duplex halftones with the Canon Pro9500 inkjet printer on symmetrical, supercalendered, nonfluorescent paper APCO II from Scheufelen Company, Germany. Classical rotated cluster halftoning at 120 lpi was used for the recto and verso layouts. The CIELAB ΔE_{94} color distance between measured and predicted spectra is used to assess the prediction quality. This metric gives an interpretable scale for accuracy assessment: we will consider that the prediction is good when the average ΔE_{94} value is lower than 1.

We printed 64 different duplex halftone colors and measured the transfer factors of each of them with the X-rite Color i7 spectrophotometer. The calibration of the DPRT model was performed by using no ink spreading function and by using ink spreading functions obtained through the minimization methods 1, 2 and 3 described above. The methods 1 and 2 may be applied in reflectance mode by considering the predictive formula of reflectance and reflectance measurements; these equations may also be applied in transmittance mode.

Table 1 presents the average ΔE_{94} values, over these 64 patches, computed between the measured spectral reflectance and the ones predicted spectra with the DPRT model by using the different calibration options. Recall that except the effective coverages necessary to compute the ink spreading functions, no other free parameter is fitted. Without ink spreading functions, the model is more accurate in transmittance mode than reflectance mode. With ink spreading functions, its prediction accuracy is comparable in both modes. It therefore seems that the effect of the ink spreading functions is stronger in reflectance mode than in transmittance mode.

Good prediction accuracy is achieved with the three minimization methods, the best accuracy being achieved with the equation based on the ΔE_{94} value. However, if we want to predict both reflectances and transmittances of duplex primaries by using single calibration, one can use the minimization method 3 which yields almost as accurate predictions as those yielded by method 1.

Table 1. Spectral and color differences on 64 duplex patches*

Minimization	Reflectance	Transmittance
none	1.33 [a]	1.12 [b]
1	0.79 [a]	0.86 [b]
2	0.66 [a]	0.77 [b]
3	0.78 [c]	0.93 [c]

* *Average ΔE94 value*
The ink spreading functions are computed from: a) reflectance measurements, b) transmittance measurements and c) both reflectance and transmittance measurements (matrix minimization method).

6. Visual application: multi-image printing

The objective in this application was to display two different binary patterns "A" and "B" in reflectance and transmittance modes, such that pattern "A" is visible in reflection mode but not in transmission mode, and pattern "B" is visible in transmission mode but not in reflection mode.

By denoting as *A* and *B* the areas filling respectively the patterns "A" and "B", and as *A'* and *B'* their respective complementary areas, the recto and verso layouts contains four areas corresponding to the areas $U = A \cap B$, $V = A \cap B'$, $X = A' \cap B$, and $Y = A' \cap B'$. These four areas are represented in Figure 4 by, respectively, red, green, blue and grey tones.

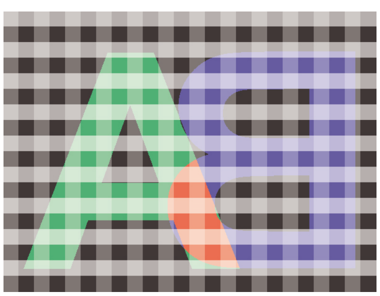

Figure 4: Mains areas of the duplex halftone print. Each colored area in this image represents a pair of recto and verso colors to be printed on the two faces of the paper.

On the recto face, each of the four areas *U, V, W* and *Y*,is filled with a checkerboard texture of four colors, respectively denoted as C_{ui}, C_{vi}, C_{xi} and C_{yi} $(i = 1,...,4)$ and featured in Figure 4 by the four different lightnesses of each tone: light, middle-light, middle-dark, and dark. Each color is determined by a set of surface coverages for the cyan, magenta and yellow inks. Since the observer sees only this face in reflection mode, only the "A" pattern should be visible. This means that the pairs of colors C_{ui} and C_{vi} $(i = 1,...,4)$ should be perceptually similar, i.e. their difference should be below the just noticeable color difference, assumed to be assessed by a ΔE_{94} value of 1. Since no metamerism effect can be produced in CMY printing, the amounts of cyan, magenta and yellow inks printed in order to obtain a pair of colors C_{ui} and C_{vi} should be similar. Likewise, the colors C_{xi} and C_{yi} $(i = 1,...,4)$ should be perceptually similar. We thus have, for each *i*,

$$\begin{aligned} \Delta E_{94}\left(C_{ui}, C_{vi}\right) < 1, \\ \Delta E_{94}\left(C_{xi}, C_{yi}\right) < 1. \end{aligned} \tag{11}$$

In transmission mode, we want that areas U and X have a uniform color denoted as C_B and areas V and Y have a second uniform color denoted as $C_{B'}$. The checkerboard texture should disappear. According to the constraints explained above, the colors in the layout of the verso face, denoted as $C'_{ui}, C'_{vi}, C'_{xi}$ and C'_{yi} $(i = 1,...,4)$, should satisfy the following properties: For each *i*,

$$\begin{aligned} \Delta E_{94}\left(C_{ui} \oplus C'_{ui}, C_B\right) < 1, \\ \Delta E_{94}\left(C_{xi} \oplus C'_{xi}, C_B\right) < 1, \\ \Delta E_{94}\left(C_{vi} \oplus C'_{vi}, C_{B'}\right) < 1, \\ \Delta E_{94}\left(C_{yi} \oplus C'_{yi}, C_{B'}\right) < 1. \end{aligned} \tag{12}$$

where symbol $C_1 \oplus C_2$ represents the color observed in transmittance mode when colors C_1 and C_2 are printed on the recto and verso faces, respectively.

In practice, we may first choose the eight colors C_{ui} and C_{xi}. From them, the eight colors C_{vi} and C_{yi} are calculated by respecting Eq. (11), for example by increasing the CMY values of the colors C_{ui} and C_{xi} by one or two units (over 100). Then, the colors C'_{u1} and C'_{x1} are chosen for the verso face, and the colors $C_B \equiv C_{u1} \oplus C'_{u1}$ and $C_{B'} \equiv C_{x1} \oplus C'_{x1}$ that will be perceived in transmission mode can be predicted. All the other colors on the verso layout are calculated by finding the CMY values c_j, m_j, y_j satisfying relations (12). Figure 5 shows a sample produced according to this method where the "A" and "B" patterns represent the words "CPGE" and "IOGS" respectively.

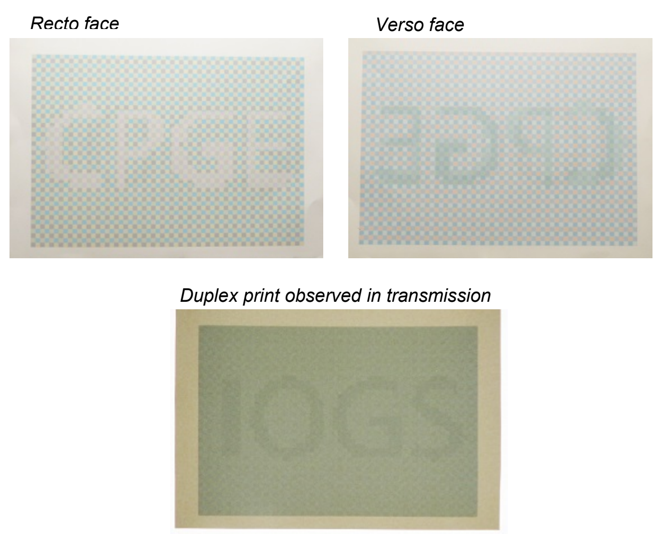

Figure 5: The inversion of the model enables to calculate the color images to print on the recto and verso sides (left and right) in order to obtain a targeted color image in transmission (center).

7. Conclusions

The duplex primary reflectance-transmittance model is an original approach allowing simultaneous predictions of the spectral reflectance and transmittance of halftone prints with good accuracy, from a fully numerical matrix calibration permitted by the flux transfer matrix formalism. Our experiments based on inkjet prints shows that the double-mode calibration is slightly less accurate than the reflectance-only calibration mode for reflectance predictions, or the transmittance-only calibration mode for transmittance predictions, but it remains satisfactory since the average ΔE_{94} value computed between the predicted and measured spectral reflectances and transmittances is below 1, which is typically considered as a good performance in the color reproduction domain.

Compared to the more classical approach consisting in making calibration and predictions in either reflectance mode or transmittance mode, which usually yields different ink surface coverages in the two modes for a same halftone, the matrix model enables obtained same ink surface coverages in the two modes, which is an advantage in advanced application for graphical arts where the recto and verso colors need to be computed in order to achieve specific visual effect. One example of visual effect presented in this paper is where two different images are displayed according to whether the light source is in front of the print or beside it. From this idea, one may imagine innovative billboard or signage displaying different images according to whether they are illuminated from outside during the day or from inside at night.

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Dr Thierry Fournel is a Professor at Lyon Saint-Etienne University in France where he received his PhD in image processing in 1991. In the first decade, his research works were devoted to particle image velocimetry and granulometry for fluid mechanics. Today, his topics are mainly related to image coding and printing especially for image-based security in addition to teaching applied information theory and image modelling.