

Automatic Spot Color Matching Using In-line Densitometric Measurements

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Abstract

In many applications a very accurate color needs to be achieved in print. In industrial printing this applies often to product colors which have to be consistent across printing sessions of the same product and across printing technologies (e.g. packages, labels, banners, and adds of the same product). In Enterprise printing this can apply to company logos. Currently few solutions are possible: One solution is using special inks. However, the design of the ink is not always feasible, and may be very expensive. The most common is the use of special color conversion tables. However, in most cases the accuracy of these tables is not perfect over the whole color gamut and further tweaking must be performed in order to achieve better accuracy, which increases the setup time for each job.

We propose a method for spot color printing using the set of available inks on the press. Our method is an iterative scheme that contains a feedback from a simple In-Line Densitometer (ILD) located in the paper path of many industrial presses after the printing engine (all our experiments have been conducted on HP Indigo presses). Required colors are specified by their Lab values. In each iteration a new coverage is printed and measured by the ILD, the algorithm calculates the change in coverage that is estimated to provide an output that is likely closest to the target Lab values required by the user. Initial results show the achieved mean accuracy for in-gamut colors is less than 1 ΔE . This accuracy is achieved for various paper types without any need to pre-define the paper type or other parameters.

Introduction

Color accuracy is a critical performance specification of a printing device. The industry-standard method of measuring color differences is called ΔE , a value less than 1 is considered perceptibly the same, and in many applications such accuracy is required. Company logos are an example of this kind of required precision. Another example is when matching should be achieved across printing devices, either when one device is used to complete a run started by another printing device or when several print products are used together (package, inlet and label in the same product). One of the most demanding applications that require high accuracy (possibly the highest) is when a label is required to match the color of the actual product (usually a color of some sort), this is the case when printing labels for ink cans, wall paint cans, hair dye, etc.

The interest in achieving more accurate spot colors is wide and common throughout the printing industry. The HP Professional Pantone Emulation (PPE) tool [1] imitates color experts in evaluation of the closest in-gamut color for spot colors that are out of gamut and thus reduces time and costs. A different appli-

cation [2] describes a technology called Digital Swatch Books, which aims to provide professional graphic designers as well as less experienced users who need to make color choices with a tool that has both a look-and-feel they are used to (i.e. that of a color swatch book) and that provides them with information on the basis of which they can make informed choices. All those methods relate to the same market need - the use of accurate colors, but do not relate to the same market segment - print shops. In order to reproduce the color that the users of the above methods specified, a print shop has to toil manually, use the time of color experts and waste consumables, not to mention the need to repeat the same as presses drift. The method we suggest is fully automated and requires a few minutes of regular press operators - no need of spectrometers or ICC profiles. It is totally automatic in the sense that all measurements are in-line, and the only required input is the target color specifications (*Lab* values). The output of our method is the optimal coverage combination that reproduces the target color - or most resembles it in the case of out-of-Gamut colors.

Prior work

Currently several methods are used to find the coverage that matches a given target. The most common method is to use the Pantone color conversions tables. These are color conversions that were built specifically to match the Pantone swatch books. However, in some cases, due to many reasons (press variability, inks variability, different substrates, etc) the first 'hit' of the color, using the given dot area (DA) values of the conversion will produce a result that can be improved (see the results of the default coverage in Table 1). This improvement is usually done by a long manual iterative procedure involving color experts using an external measuring device or by a visual matching to the target color, increasing the set up time for each job. In cases where the desired color is not part of the Pantone swatch book the regular conversions that are used produce even less accurate result. Another solution is to use special inks, with the exact color of the desired target. This can be an acceptable solution for customers who need to print only very few colors and who perform long runs with this ink. In any case, this requires an additional ink to support and maintain in the press and additional separation per job (with additional costs). In cases where several colors are needed within a job, or for short runs, each with a different color, this solution is not acceptable.

Our approach

The general scheme of our method is as follows. The press prints the first print using the values from the conventional (Pantone or regular) color tables, or some other (even random) cover-

age combination. The ILD measures the Optical Density (OD) of the patch, and the algorithm produces the new coverage for each of the inks to be printed in the next iteration. In addition the algorithm estimates the ΔE difference between the desired color and the printed patch. When converging (the suggested changes in the coverage are negligible or after a fixed number of iterations), the combination that was estimated by the algorithm as closest to the target is chosen to fit the customer request.

The biggest advantage in the suggested method is in reducing the set up time for these kind of jobs dramatically. If today most of the set up time is dedicated to match the accuracy of the colors, which can range from a few minutes to an hour (and in some cases even more) to seconds (maybe up to a minute). In addition, currently the operator or the pre-press people are required to know how to perform this fine tuning of the colors. Using the suggested solution can free the operator and the pre-press people from these tasks, making the procedure fully automatic and assuring accurate results, independent of the operator skills.

Detailed Solution

We are given *Lab* color specification values $\mathbf{L}_t = [L_t, a_t, b_t]^T$. Our goal is to use the available inks of the press in order to reproduce the target color, or in case it is out of gamut for that press, produce a color which is closest (perceptually) to the target. To that end, we use the measurements \mathbf{m} of the In-Line Densitometer (ILD), which is located in the paper path of the press after the printing engine. The ILD or similar devices are part of many industrial and commercial presses, specifically, it exists on all HP Indigo presses, to control press ink densities. In order to translate between measurements and target *Lab*, we use the spectral reflectance value \mathbf{s} .

Let $\mathbf{s} \in \mathbf{R}^k$ be the spectral reflectance vector of a printed patch. Usually \mathbf{s} is a vector representing the average reflectance in 10nm intervals in the visual spectrum range (380nm-730nm), in which case $k = 36$. The ILD measurements $\mathbf{m} \in \mathbf{R}^3$ are projections of the reflectance spectrum of the printed patch, \mathbf{s} , on 3 filters $P \in \mathbf{R}^{3 \times k}$ of the ILD, so that $\mathbf{m} = \mathbf{P}\mathbf{s}$. The *Lab* values of \mathbf{s} are computed from its projections on the 3 Color Matching Functions, $\mathbf{CMF} \in \mathbf{R}^{3 \times k}$. These projections are referred to as the XYZ values, $\mathbf{x}_s \in \mathbf{R}^3$ of \mathbf{s} , thus $\mathbf{x}_s = \mathbf{CMF} \cdot \mathbf{s}$. The translation between the ink coverage and the spectral reflectance is done using a color model. Throughout this work we assume the cellular Neugebauer model [3] $N(\mathbf{c}) = \mathbf{s}$ that estimates \mathbf{s} as a linear combination of pivot spectral reflectance values (given as parameters to the model), where the coefficients of this combination are computed according to the coverage values $\mathbf{c} = [c, m, y, k]^T$. The Neugebauer model was proved accurate to represent HP-Indigo press outcome. Other models for other printing technologies or devices are possible. The accuracy achieved by using the model depends on the validity of its parameters, and changes in the ink/media/press state may cause loss of accuracy. Therefore, it would have been best to define a new parameter file before each execution of the algorithm. However, this is completely impractical, as it requires the use of an accurate spectrometer, which prevents an automatic process. Moreover, we decided to limit ourselves to **one** parameter file, measured once (about two years ago) on a coated paper

¹Throughout this work we assume only 4 inks - cyan, magenta, yellow and black. Generalization to more inks is possible

stock, and use this file for all presses, all batches of ink and all media types. This was done for simplicity reasons, and also in order to eliminate the need of operators to define the type of media they work with. The algorithm described next was designed in order to overcome this difficulty, and achieve a good accuracy despite the in-accurate parameters it uses. We next present two different approaches we applied for this problem sequentially.

A: Difference coverage improvement algorithm

The first solution we suggest is the following. First, estimate the coverage of the given patch and its ΔE difference from the target. Such an estimation based only on the ILD measurements is possible when assuming the color model as a prior for all expected outcomes of the press [4]. Searching the space of possible outcomes we look for the one with the closest ILD measurements. We solve for the spectral reflectance \mathbf{s} and the coverage \mathbf{c} ,

$$F_1(\mathbf{s}, \mathbf{c}) = \|\mathbf{N}(\mathbf{c}) - \mathbf{s}\|_2^2 + \lambda \|\mathbf{P}\mathbf{s} - \mathbf{m}\|_2^2. \quad (1)$$

Notice that if the parameter files we use was optimal, we would expect the coverage combination \mathbf{c} to be identical to the actual printed coverage \mathbf{c}^p . However, due to the invalidity of the parameters, the value of \mathbf{c} is different, but still very important for the following steps of the algorithm. Also in this stage we compute the ΔE difference between \mathbf{s} and the target color.

In the second stage we estimate the coverage likely to best minimize the difference from the target color (described in the next sub section). Finally, we produce as output the **difference** between the two sets of coverages, added to the last printed coverage (that is, the next coverage to be printed). The outline of this solution is summarized in Figure 1.

Input: Target *Lab* values (L_t) and initial coverage combination $\mathbf{c}_0^p = [c_0^p, m_0^p, y_0^p, k_0^p]$.
 For $j = 0, 1, 2 \dots N$, do:

1. Print \mathbf{c}_j^p . Let \mathbf{m}^j be the ILD measurements.
2. Solve: $F_1(\mathbf{s}^j, \mathbf{c}_j) = \|\mathbf{N}(\mathbf{c}_j) - \mathbf{s}^j\|_2^2 + \lambda \|\mathbf{P}\mathbf{s}^j - \mathbf{m}^j\|_2^2$ (See [4] for a possible numerical approach).
3. Estimate ΔE difference between L_t and \mathbf{s}^j .
4. Solve: $F_2(\mathbf{c}_{j+1}) = \operatorname{argmin}_{\mathbf{c}_{j+1}} d(\mathbf{N}(\mathbf{c}_{j+1}), L_t)$, for a distance metric d , start with the initial combination: (\mathbf{c}_j) (see next).
5. Set $\mathbf{c}_{j+1}^p = \mathbf{c}_j^p + \mathbf{c}_{j+1} - \mathbf{c}_j$

Figure 1. A description of the difference coverage improvement algorithm

For describing the minimization step (F_2), we use two different approaches. The first minimizes the XYZ difference, and allows a more specific numerical solution due to the relative simplicity of the problem. The second uses an optimization function to minimize the LAB difference, and is specific for out-of-gamut colors.

A1: Minimization of the XYZ difference: For estimating the next potential coverage we solve,

$$\mathbf{c} = \operatorname{argmin}_{\mathbf{c}} \|\mathbf{CMF}(\mathbf{N}(\mathbf{c})) - \mathbf{X}_t\|_2^2 \quad (2)$$

where $\mathbf{X}_t \in \mathbf{R}^3$ are the target XYZ values (computed directly from L_t). For solving Problem 2 we adopt the technique suggested in [4], in which we linearize the Neugebauer model $\mathbf{N}(\mathbf{c}) = P_\Lambda B\mathbf{x}$, where P_Λ is a matrix that holds as columns all spectral reflectance

values used for the model parameters, \mathbf{B} is a 16×16 matrix of zeros, 1 and -1 , and

$$\mathbf{x}(\mathbf{c}) = [1, \mathbf{c}(1), \mathbf{c}(2), \mathbf{c}(3), \mathbf{c}(4), \mathbf{c}(1)\mathbf{c}(2), \mathbf{c}(1)\mathbf{c}(3), \mathbf{c}(1)\mathbf{c}(4), \mathbf{c}(2)\mathbf{c}(3), \mathbf{c}(2)\mathbf{c}(4), \mathbf{c}(3)\mathbf{c}(4), \mathbf{c}(1)\mathbf{c}(2)\mathbf{c}(3), \mathbf{c}(1)\mathbf{c}(2)\mathbf{c}(4), \mathbf{c}(1)\mathbf{c}(3)\mathbf{c}(4), \mathbf{c}(2)\mathbf{c}(3)\mathbf{c}(4), \mathbf{c}(1)\mathbf{c}(2)\mathbf{c}(3)\mathbf{c}(4)]^T. \quad (3)$$

and solve in iterations,

$$F(\mathbf{c}) = \|\mathbf{CMF} \cdot P_{\Lambda} \mathbf{B} \mathbf{x}(\mathbf{c}) - \mathbf{X}_t\|_2^2 \quad (4)$$

Minimizing F with respect to \mathbf{c} is done by minimizing with respect to \mathbf{x} , and projecting \mathbf{x} into to proper subspace. The scheme is summarized in Figure 2

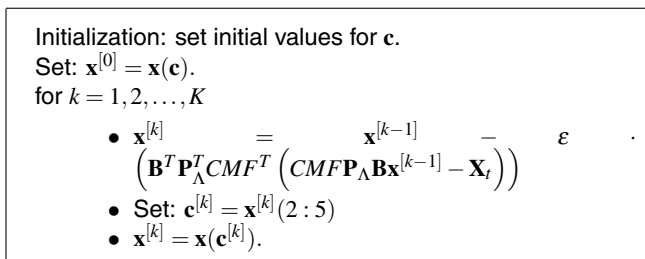


Figure 2. Solution scheme for Problem (2)

A2: Minimizing the LAB difference: For out-of-gamut colors the minimization of the XYZ difference does not suffice. We use a numerical optimization procedure implemented in matlab to solve Equation 2 for the LAB space,

$$\mathbf{c} = \operatorname{argmin}_{\mathbf{c}} \|\mathbf{XYZ2LAB}(\mathbf{CMF}(\mathbf{N}(\mathbf{c}))) - \mathbf{L}_t\|_2^2. \quad (5)$$

B: Linear combination of recent coverages

Applying the *difference coverage improvement algorithm* we witnessed that the accuracy in the coated paper was much better than the one achieved on Matte. This was explained by the fact that the parameters we use for the cellular Neugebauer model were measured on a coated paper, and therefore were more adequate for it. As written before, we decided not to use another parameter file, which would make the algorithm more complicated, and would require the user to define the type of paper he works with. We therefore tried to use some different information that we have and do not take advantage of - the previous iterations.

In each iteration we print some known coverage combination, and receive its ILD readings. The pair of coverage and its ILD readings is valid specifically for the current state of the press (the exact ink, paper, mechanical properties etc.). Also, the algorithm provides us with an estimation of the full spectrum of the printed patch, and as a result, its XYZ and Lab coordinates. This estimation depends on the parameter file we use, and therefore might be not accurate enough. However we saw that it more or less preserves the order of the distances to the target Lab. That is, if one patch is estimated by the algorithm to have closer Lab values than another, its distance is indeed closer. With this assumption in hand, we again apply a piecewise linear interpolation (just as being done in the regular Neugebauer model, only now

we set the pivot points) in order to compute the coverage that is likely to result a color closest to the target specification.

Specifically, we are given a set of coverages, arranged as rows in the coverage matrix $\mathbf{C} = [\mathbf{C}_1; \mathbf{C}_2; \dots; \mathbf{C}_k]$, ($\mathbf{C}_i = [C_i^c, C_i^m, C_i^y, C_i^k]$) and their estimated XYZ coordinates matrix $\mathbf{X} = [\mathbf{X}_1; \mathbf{X}_2; \dots; \mathbf{X}_k]$, ($\mathbf{X}_i = [X_i^x, X_i^y, X_i^z]$) (the estimation depends on the parameter file we used). We would like to derive a new coverage that is potentially closer to the target. we find a coefficient vector $\alpha \in R^k$ that construct the affine combination,

$$\min_{\alpha} \|\mathbf{X} \cdot \alpha - \mathbf{X}^t\|_2^2, \quad \text{subject to } \mathbf{1} \cdot \alpha = 1, \quad (6)$$

where $\mathbf{1} \in R^k$ is a vector of ones.

We apply this coefficient vector on the coverages matrix in order to get the new coverage C_{k+1}^p to be printed,

$$C_{k+1}^p = \mathbf{C} \cdot \alpha. \quad (7)$$

In practice, because we work in dimension 3, it suffices to consider only 4 combinations, and indeed, we choose from the $\binom{k}{4}$ possible solutions the set that constructs the tetrahedrons with the smallest angles.

Algorithm Description Summary

Each execution of the algorithm includes applying the two methods sequentially. The *difference coverage improvement algorithm* (A) is used first (with either XYZ or LAB minimization or both, sequentially), and then, the *linear combination of recent coverages* (B) method is applied from the seventh iteration, or sooner, if the algorithm converged (convergence is considered when $\Delta C \approx 0$). Each iteration provides as output the new coverage to print, and an estimated ΔE different of the last print from the target. After conducting a total of 12 iterations, the algorithm ends, and the coverage combination which resulted the best estimation (closest to the target) is chosen as the solution.

Results

Pantone Idx	Ink A (in ΔE)		Ink B (in ΔE)	
	Default	Resulted	Default	Resulted
193	2.4478	0.9288	1.3195	0.4497
440	1.2186	1.2438	1.1414	0.8575
7413	1.1461	0.5417	2.21	0.4448

Result summary for 3 in-gamut Pantone colors printed on gloss, using two different batches of ink.

Initial tests of the algorithm were conducted using both coated and uncoated paper. We present in Table 1 the results of 6 experiments that were done on 3 different pantone colors on gloss paper, using two different batches of ink (while the model parameters were measured a year before on a different press, with a different batch of ink). The 'default' coverage combination is the one recommended by the Pantone color conversion tables. Notice that in all these experiments our algorithm achieves equal or better accuracy than the default solution (in one experiment the accuracy reduces from $1.22\Delta E$ to $1.24\Delta E$ which in all aspects is

considered the same accuracy)². Actually, in 5 of these 6 experiments the achieved accuracy is substantially better, as it crosses the $1\Delta E$ threshold. Similar experiments done on an uncoated paper (using the same parameter file that was measured on gloss) are presented in Figure 2 and show results of below $1\Delta E$ difference.

The automatic approach for spot color reproduction is currently being implemented on an Indigo press for further comprehensive testing and utilization. Future experiments will include more colors printed on more types of substrates.

Color	Target Lab Values			Default	resulted
	L	a	b	ΔE	ΔE
Bright green	65.79	-40.03	-1.69	2.53	1.24
Bright orange	69.4	36.51	51.9	1.46	0.91
Dark blue	41.82	9.22	-40.15	2.19	0.81
Medium purple	40.04	22.45	-36.36	2.07	1.07
Pantone 137CS	57.64	0.17	44.01	1.38	0.70
Strong red	52.1	63.17	1.48	3.36	1.56

Result summary for 6 colors printed on matte. The default values are the ones that generated a zero ΔE difference only 2 months before this experiment was performed.

Summary

We have described a novel algorithm for automatic spot color matching that uses Inline densitometer measurements in order to tune the coverage values to match a specific *Lab* requirements. We described here two different algorithms for this problem - *Difference coverage improvement algorithm* and *linear combination of recent coverages algorithm*, and described an improvement for minimizing in the Lab color space.

Currently, we are facing more comprehensive tests of the algorithm in order to decide the final configuration for its execution on the press. However, the results so far are promising as to the potential for automatic process for best coverage detection application.

References

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²All ΔE values in this paper are $\Delta E - 00$ values, measured by an accurate spectrometer