Simulation of Prints Made with Océ's 7 Color Direct Imaging Printing Technology

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Abstract

In Océ's Direct Imaging (DI) technology 7 mono-component color toners are used for full color printing, as described at previous NIP conferences [1,2,3,4]. In this paper, a simulation model of the DI print process is presented which was developed to determine the relation between print parameters and the image quality for any given arbitrary full-color digital input file. The model consists of four modules which describe development, transfer, fusing and optical characteristics of toner dots on paper. Because a purely theoretical approach would take too much calculation time, the model is semi-empirical using input parameters such as toner particle size distribution, magnetic fields and halftoning algorithms. It will be shown that the model can predict the visual appearance and image quality attributes of prints in good agreement with experimental results. Evaluation of image quality takes place by visualising enlarged sections of simulated prints on either a calibrated monitor or on paper after printing with a calibrated printer.

Introduction

From 2001, Océ successfully applies the unique Direct Imaging (DI) printing technology in its Color Production Systems (CPS). In this digital full-color technology, seven mono-component, electrically conductive, magnetizable color toners are employed. A global representation of the DI-process is shown in Figure 1.

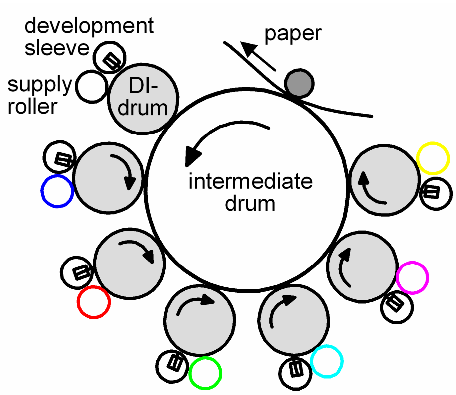

Figure 1: *Schematic representation of the DI-printing process.*

Seven mono-color toner images are developed in seven DI-units which each comprise of a supply roller, a development sleeve and a DI-drum. After development on the DI-drum surface, each single color toner image is adhesively transferred to a rubber coated central intermediate drum (IM). Finally, the total image is transferred and fused to paper in a single step applying pressure and heat.

As a design tool for image quality improvement of the Direct Imaging technology, a printer simulation model has been developed. By accurately simulating the printing process, the model predicts the visual appearance of any given color image as a function of print parameters such as halftoning algorithm and toner particle size.

Printer Model

The model consists of four main modules as illustrated in Figure 2: development, transfer, transfuse and color model. The digital original can be any full-color file on a PC. Offline image processing software provides for a print-file that can be sent to a real DI-printer as well as to the printer model. The data flow between the model modules consists of seven color bitmaps containing toner coverage information per pixel. The final output file comprises one bitmap with a color spectrum for each pixel, which can be calculated to XYZ color coordinates.

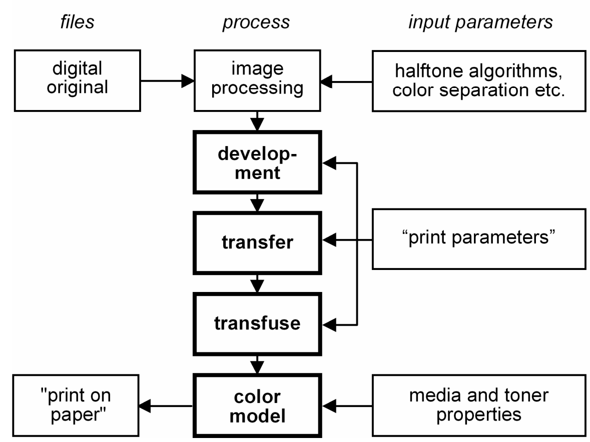

Figure 2: *Flowchart of the DI-printer simulation model showing the model modules.*

In the next chapters, an explanation of each step in the DI print process will be given, followed by a description of the relevant model module. Because of the extensiveness of the model, some details will be left out of this description.

Development: printer

The DI development process consists of a supply nip (distance supply roller - DI-drum approx. 1 mm) and a development nip (distance development sleeve - DI-drum approx. 150 μm), as illustrated in Figure 3. In the supply nip, toner particles (radius approx. 5 μm) are continuously developed on the surface of the DI-drum and transported towards the development nip, where toner is either printed or cleaned.

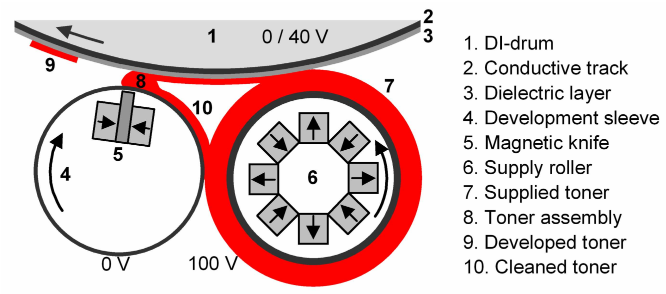

Figure 3: *Schematic representation of the DI development process.*

The supply-roller consists of a stationary magnetic core surrounded by a rotating metal shell. The electrically conductive and magnetizable toner particles are supplied and brought into contact with the surface of the DI-drum. The DI-drum consists of individually addressable circumferential electrodes, "tracks", which are covered with a dielectric top-layer. Due to an electrical potential difference between the supply roller surface and the tracks of the DI-drum, toner particles and the tracks beneath the dielectric layer will obtain an equal, but opposite, charge (comparable to charging a capacitor). The resulting electric force acting on toner particles towards the surface of the DI-drum is larger than the magnetic force towards the supply roller. This way, toner particles are continuously developed on the DI-drum surface and transported towards the development nip.

In the development nip a thin conductive sleeve rotates around a stationary magnetic geometry. This so called "magnetic-knife", has been designed to produce a strong localized magnetic field with a very high gradient. Toner particles that enter the development nip become magnetized and are magnetically pulled from the drum surface towards the sleeve. They are transported back to the supply roller by the rough surface of the sleeve. This situation, when a track is kept at 0 V, is called the "cleaning state". An equilibrium situation arises where an equal amount of toner enters and exits the development nip. This leads to an approximately constant number of toner particles in the development nip, which is called "toner assembly".

Whenever a track is switched to a voltage of 40 V, toner particles near the DI-drum are inductively charged by the same mechanism as described for the supply nip. In this "printing state", the sum of adhesion and electrical force towards the DI-drum becomes larger than the magnetic cleaning force towards the development sleeve: toner particles are developed on the surface of the DI-drum. The axial and tangential resolutions of the developed image are determined by the track pitch and the timing of the print voltage per track. For the CPS900 these are 600 dpi and 2400 dpi respectively.

Because the DI-drum rotates at a constant speed, time directly translates to a distance covered in the process direction by the surface of DI-drum. A track that is switched to a print voltage will not instantly be completely covered by toner particles. The distance needed to achieve full coverage is called edge sharpness. An example of how toner coverage follows the print voltage following the process direction x is shown in Figure 4. The print voltage is switched on for a distance a, resulting in toner development on the addressed track. The coverage profile in the middle of the figure expresses the average toner coverage *cov(x)* on the track as a function of the process direction x (average of approx. 50 sample dots). The coverage profile of a single printed dot would not look so smooth. The difference between the base length of the voltage and coverage profile is called line broadening Δa. A CCD-recording of developed toner particles on the surface of the DI-drum is shown.

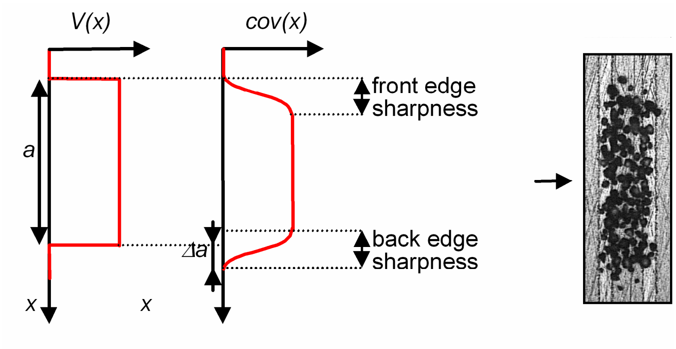

Figure 4: *A print voltage signal on a track (left) is transformed into an average toner coverage profile (middle). To the right, a CCD-recording of a developed dot on the surface of the DI-drum is shown.*

Development: model

Just before a finite surface element of the DI-drum leaves the edge of the toner assembly, it is decided how many toner particles are developed on that element. The complex behavior of the toner assembly has been described in a DEM-model [2]. This model could theoretically be used to predict toner development on large areas of the surface of the DI-drum. However, this would be far too time consuming. Therefore, a relatively straightforward statistical model is used to predict coverage variations due to complex interactions in the toner assembly. To simulate the amount of toner developed in a pixel area, the following assumptions are made:

- The average coverage per pixel is equal to the "print-probability" of toner particles being developed on that pixel.
- The print-probability is equal for every surface element within a pixel.
- The print-probabilities within a pixel are independent.

Based on these assumptions a binomial distribution can be assumed:

$$f(n,x) = \binom{m}{n} \mathrm{cov}(x)^n (1-\mathrm{cov}(x))^{m-n} \tag{1}$$

The binomial distribution describes the probability that exactly n toner particles are developed in a pixel at position x. m is the maximum number of toner particles that fit inside a pixel, which is calculated from pixel size, particle size and a stack factor (approx. 0.9).

The standard deviation of the average coverage is given by:

$$\sigma_{\text{cov}}(x) = \sqrt{\frac{\text{cov}(x)(1 - \text{cov}(x))}{m}} \qquad (2)$$

Figure 5 illustrates the effect of m on coverage variations. A smaller toner diameter results in less coverage variation between pixels.

The binomial distribution only provides for a discrete number of particles to be developed on a pixel. In reality, toner particles have a particle size distribution and can be developed on edges of a pixel, so a continuous coverage is needed. Therefore, coverage is selected from a normal distribution around the average coverage *cov(x)* with standard deviation $\sigma_{cov}(x)$ as is shown in Figure 5.

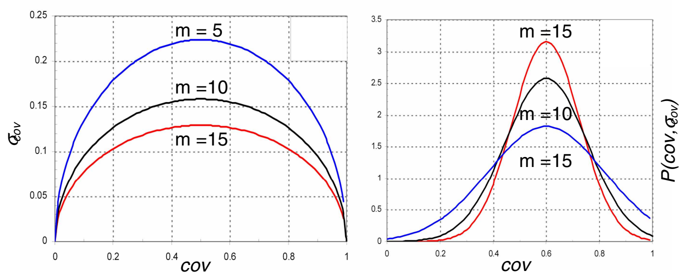

Figure 5: *Left, the spreading on coverage as function of the average coverage for* m *= 5, 10, 15. Right, The normal distribution for cov(x) = 0.6 for m = 5, 10, 15.*

The increase and decrease regions of coverage profiles, as well as the line broadening of average coverage profiles, are independent of the addressed lengths *a*. The average coverage profile of a developed dot can be approximated by a trapezium profile, given the front and back edge sharpnesses and the line broadening as input parameters. These input parameters can be easily empirically determined for any printer configuration, i.e. for different magnetic knife types or sleeve speeds.

Now, it will be shown how this statistical model is implemented to calculate toner coverage of pixels inside a dot. The coverage selection process for a pixel at position 2 within a dot with a total length of 7 pixels is represented in Figure 6.

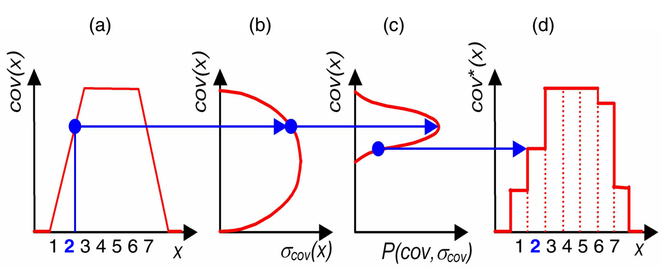

Figure 6: *Statistical coverage selection process from average coverage profiles, to standard deviation, to normal distribution, to selected coverage Profile representing toner coverage per pixel on the surface of a DI-drum.*

First, the average coverage profile is calculated for the entire dot, leading to an average coverage for each pixel within the dot. Subsequently, the spreading on the coverage is determined per pixel using formula (2) as depicted in Figure 6(b). Then, the corresponding normal distribution is calculated as illustrated in Figure 6(c). From this distribution a coverage *cov*(2)* is drawn for the particular pixel at position 2. The end result after evaluation of all positions within a dot is a coverage profile for the evaluated dot (depicted in Figure 6(d)). For each of the seven colors, a bitmap is filled with coverage data representing toner coverages for all pixels on the surface of each DI-drum.

This model module has been validated by comparing simulations with measured dot coverage profiles on the DI-drum surface using a high speed CCD camera. An example of such a validation result is shown in Figure 7. It is shown that the average coverage (averaged across many measured dots) can be predicted in good agreement with the measurement and that the assumed statistical model is sufficient for the prediction of coverage variations (between dots) on the surface of the DI-drum.

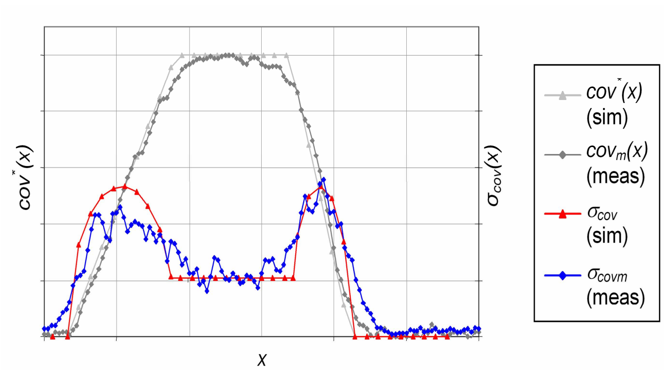

Figure 7: *Validation of the simulation of color toner development on the surface of the DI-drum.*

Although not included in this article, the development module also incorporates axial coverage profiles arising from the transitions from track to track (more information about the electrical effects occurring in axial direction can be found in [4]).

Transfer: printer

After development, the seven color toner images are subsequently transferred from the surface of each DI-drum to the rubber surface of an intermediate drum. In this step toner particles are still attracted towards the drum surface by electrical and adhesion forces. Because of high toner-rubber adhesion and low toner-toner adhesion, only toner particles that have direct rubber contact will be transferred to the intermediate drum. This is illustrated in Figure 8: yellow (light) toner particles will only be transferred to "empty" areas of the intermediate surface.

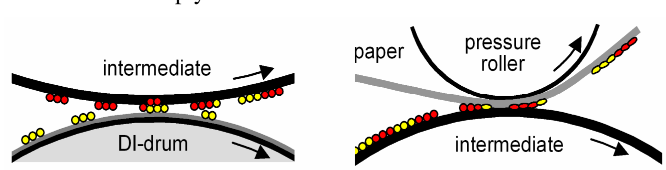

Figure 8: *Left a schematic representation of the complementary transfer principle, right a schematic representation of the transfer and fuse nip.*

This collection principle is called "complementary transfer" and provides for full-color mono-layer toner images with perfect color-adjacency (trapping algorithm with some overlap is used, leading to no "white" between adjacent colors). The loss of toner coverage due to the overlap between toner images, is taken into account by adressing additional coverage during image processing.

Transfer: model

The seven bitmaps with coverage data are collected in the order as applied in the printer: KRMBCGY. Because the black toner image is the first to be transferred, the probability that toner particles are transferred from a pixel on the DI-surface to a corresponding destination pixel on the intermediate surface is 100%. However, the transfer probability per pixel of the following color toner images depends on the toner coverage that is already present at the destination pixel, i.e. the sum of previously transferred toner coverages. The following relation is assumed for the average transfer of toner coverage from a pixel at position x on the DI-drum surface to a corresponding destination pixel at position x' on the intermediate (IM) surface:

$$\mathrm{cov}_{IM,i}(x') = \mathrm{cov}^{*}_{DI,i}(x) \cdot \left(1 - \sum_{j=K}^{i-1} \mathrm{cov}_{IM,j}(x') \right) \qquad (3)$$

$cov_{DI,i}{}^{*}(x)$ is the to be transferred toner coverage of color i (= K to Y) on a pixel at position x on the DI-drum surface. The sum of previously transferred toner coverages on a pixel at position x' on the intermediate surface is given by $\Sigma ov_{IM,j}(x')$ with j (= K to i-1). Thus, the average transferred toner coverage for color i, $cov_{IM,i}(x')$, equals the original drum coverage times the percentage of free space on the intermediate surface. For each toner color, a bitmap with coverage data representing the toner coverage on the intermediate surface. For each of the seven colors, a bitmap is filled with coverage data representing toner coverages for pixels on the surface of the intermediate drum.

Other input parameters regarding this module are color-to-color registration errors and variations in transfer efficiency.

Transfuse: printer

Finally, the full-color mono-layer toner image is transferred and fused ("transfused") from the intermediate rubber onto paper. By applying heating (up to about 110°C) and pressure, the toner particles melt and are pressed into the paper (see Figure 8). This results in a solid robust toner layer with a thickness of approximately 5 µm.

Transfuse: model

Toner particles are considered to be homogeneous spheres with an average radius r_m. During transfuse, the spheres are pressed into a disc-shape with thickness d_{fuse}, while the volume remains constant. The ratio of area coverage after transfuse A_{fuse} and before transfuse A can then be expressed as follows:

$$\frac{A_{fused}}{A} = \frac{4 \cdot r_m}{3 \cdot d_{fuse}} \qquad (4)$$

This coverage increase is dependent on the layer thickness after fusing, and thus dependent on the toner and media type. In general, the coverage increases with about 33%. Coverage surplus within a pixel is divided amongst the surrounding pixels (1/6 to direct and 1/12 to diagonal neighbours). This module's output are seven bitmaps containing coverage values and layer thickness for each toner color.

Color model

To translate toner coverage to the perception of color, the spectral color prediction model as presented in [3] was used. This model is based on the combination of ray-tracing, Mie scattering and Monte Carlo simulation. It is applied to determine the XYZ color values of each pixel as a function of light source, toner ingredients, layer thickness, media type and toner area coverage. The model addresses effects as dot-gain, gloss and fluorescence. The output bitmap can be viewed on a color calibrated monitor or on paper after printing with a color calibrated printer.

Demo: An example of a full-color simulation

In this final paragraph, only one example of a simulation of a full-color image is shown which will be compared to the scan of a real print. In Figure 9, a scan of a real Océ CPS700 print is shown next to a simulated image using Océ CPS700 printer settings. Because of the scanner properties the color impression of the scanned print is somewhat different than that of the simulated file. Although possibly difficult to illustrate in this paper, the comparison between the two images shows that the simulated image is in good agreement with the scan of the real print.

***Figure 9:** A scan of a real Océ CPS700 print next to a simulated file using Océ CPS700 printer settings. The original picture at true size is also shown.*

The printer model has been successfully applied in many cases such as:

- Assisting in the design of new halftoning algorithms by judging visualized simulations on graininess and rendition of detail.
- Several new printer concepts that would take considerable time to realize were assessed by visualizing the potential gain in image quality.
- Insight was gained in the relation between print parameters and print quality attributes like graininess by use of the printer model.

For the future, there are still some issues to be solved regarding very short dots and the connection of long dots. In these cases the average coverage profiles deviate from the assumed trapezium shape.

Conclusion

A DI-printer model was developed with which it is possible to simulate the printed color output of arbitrary full-color originals as a function of print parameters such as edge sharpness and toner particle size. It is currently applied as a design tool to develop new image processing algorithms, to estimate the value of new printer concepts and to gain insight into relations between print parameters and image quality attributes.

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Author Biography

Jochem Brok received his MSc degree in Physics from the Technical University of Eindhoven in 2002. He then joined Océ-Technologies B.V., where he spent the first two years working in research on improvements of the Océ Direct Imaging development process with focus on print quality. Currently he is investigating novel and advanced print technologies.