Optimizing Laser Print Quality: Phase Space Modeling

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Abstract

A novel approach for modeling of laser printers is described. Other printer simulations approximate the final result on paper for relatively large printed patterns under typical conditions, many times using experimental input/output data as basis for the simulation. For the phase space simulations we use basic physics principals and model simple printed elements such as few dots or lines. Instead of modeling a large variety of printed patterns to approximate observable results we vary the physical parameters under which the simple printed elements are printed. Thus, we are able to learn the basic behavior of much larger printed structures under common and even uncommon conditions. Using the method it is possible, for example, to understand print stability control or to define requirements and tolerances for printer elements. Moreover, by understanding from basic physical laws the behavior and interactions of these simple print elements we are able to construct large scale printed elements with a-priori knowledge of the expected final results, without resorting to the large scale simulations. The method, which is applied for Liquid EP, is easily transferable to dry toner Xerography.

Introduction

Modeling of laser printers has advanced in great strides during the last years [1], [2]. The increased understanding of the physics of the systems and the abundance of experimental measurements available, combined with faster computers and simple to use modeling tools allow building better and more expansive simulations. Some of these models can accept as input a digital pattern and output a modeled physical pattern which either describes the expected output on media or depicts the perceived optical result. Most of what we have seen in these researches was aimed at building a "virtual printer". Since the requirement from these simulations is to model viable output results some of the elements are approximated using the experimentally existing data or using "fudge factors". These "virtual printers" are later used as an experimental tool. Instead of designing a set of digital data and printing it on a real device the researchers can test the output on a computer.

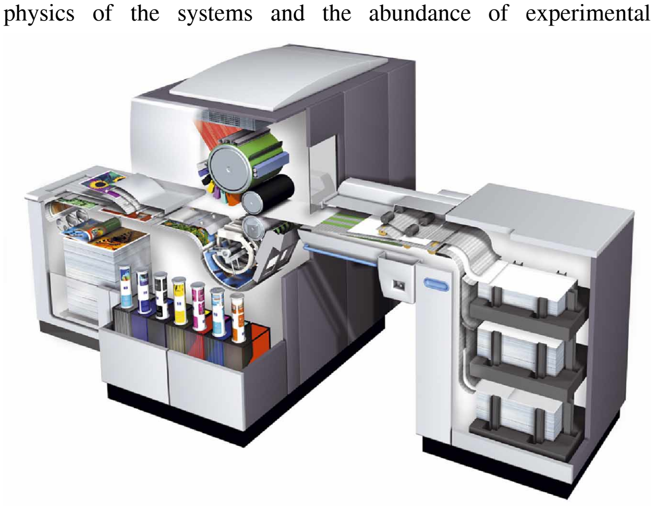

Figure 1 HP-Indigo 5000 press

Our research is intended at understanding and improving the Liquid Electro Photography (**LEP**) printing process of HP-Indigo. The models are based ONLY on physical rules which we assume and sometimes measure. Instead of enlarging the geometrical domain, by modeling larger and larger structures, we enlarge the physical domain by scanning over various parameters in the physical space and observing their combined effect on simple printed elements. The more interesting knowledge we found is when various physical parameters interact. Thus, modeling of the printers multi dimensional physical coordinates using simple print elements, hence – **P**hase **S**pace **M**odeling (**PSM**) [3] we gain deep insight into the behavior of our printing system.

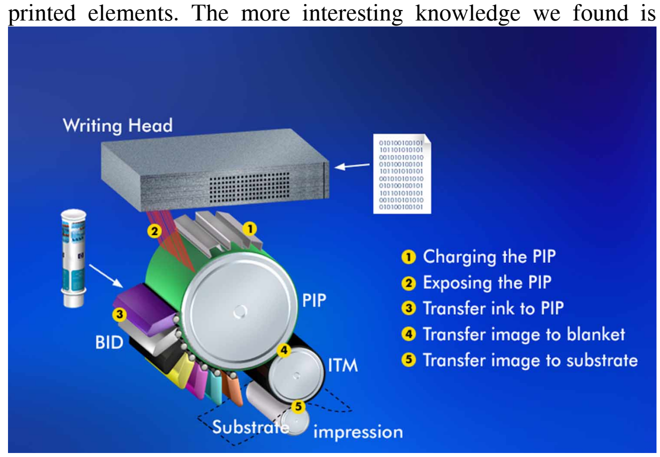

Figure 2 HP-Indigo printing engine

In what follows we will begin by describing the HP-Indigo **LEP** process, followed by a description of the basic modeling system and show, through one example, the power of modeling the multi dimensional physical space or **PSM**.

The LEP system:

The HP-Indigo process is an **LEP** process, very similar to Xerography but utilizing a liquid instead of dry toner. Figure 1 displays the HP-Indigo 5000 and Figure 2 shows the printing engine. The engine works as follows: a photoconductor (Photo-Imaging-Plate **PIP**), wrapped on a drum, roles under a set of negative charging Scorotrons. The charged PIP is then illuminated by a multi-diode scanning laser, discharging the **PIP** where light impinged on it. Next, one of up to 7 ink units (**BID**) leaves charged ink on the discharged regions of the **PIP**. The inked image on the **PIP** is carried to heated intermediate drum (blanket) and

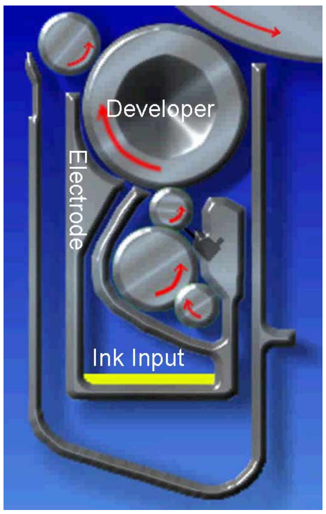

Figure 3 BID system

from the blanket to the paper. This process is done 4 times for CMYK image on one paper and more or less for, other, different color combinations.

The **BID** (Binary Image Development) unit is displayed in Figure 3. Dilute uncharged Electro Ink is introduced through the

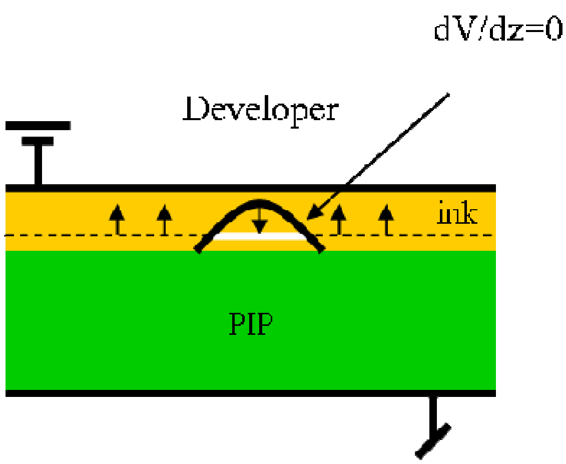

Figure 4 Schematic development nip

input and flows up the channel. As the developer roller takes the ink to the left an electric field between the electrode and the developer electrophoretically develops a thin, highly charged and very dense with solids, ink layer. The thin layer continues with the roller while the carrier liquid with remaining solid content goes back to the ink tank. Further on the squeegee roller applies both mechanical pressure and a high electrical field on the thin layer, charging it even more and extracting more of the carrier liquid. The final stage is when the thin layer enters the nip between the developer and the PIP (on the top right part).

Figure 4 displays, schematically, the development nip between the **BID** developer and the **PIP**. The back side of **PIP** is grounded and we assume no charge is trapped in the **PIP**. The charged ink is between the **PIP** and the developer and the latent image is taken as a charge internal boundary condition between the ink and the **PIP**. The voltage of the developer is set so that ink over an uncharged region on the **PIP** will be pushed predominantly towards the **PIP** and ink over a charged region will be repelled from the **PIP**, this is shown schematically by the black arrows. In terms of physical model solving for the electric potential we assume that when the **PIP** detaches from the developer the ink will split at the point where the electric field in the perpendicular direction to the **PIP** will change sign.

Development model

The basic model we use for **LEP** development is a finite element model which we built using FEMLAB (COMSOL) software [4]. The model solves the Poisson equation for the model depicted in Figure 4:

$$-\nabla^2 \varepsilon\varepsilon_0 u = \rho; \hat{n}\cdot D = \sigma \qquad (1)$$

Where ε is the dielectric constant, u the potential, ρ is the charge density in each region and σ the latent image charge. We use Dirichlet boundary conditions for the top and bottom, u=Vd and 0, and Neumann conditions σ=0 on the sides. The charge density on the ink/**PIP** interface is calculated by various methods. The simplest one is by mapping the laser exposure to the Photo-Induced-Discharge curve [5], [6] by an equation in the form of :

$$\sigma(\vec{x}) = (\sigma_d - \sigma_l)\exp\left(-\frac{LP(\vec{x})}{sense}\right) + \sigma_l \qquad (2)$$

Where σ(x) is the charge density on the PIP/ink interface, σ_d and σ_l are the dark and light charge (charge density without light and with constant illumination) and sense is the sensitivity of the **PIP**. More elaborate schemes take into account charge motion on the **PIP** due to lateral conductivity and the full development of the charge in the **PIP** including the recombination in the charge generation layer [6]. The finite element form is more flexible since it uses the COMSOL tools. Using this we tested variable charge density forms and inclusion of time dependent effects. Another form of solution which is slower to develop but faster to run solves the Poisson equation using Fast Fourier transforms [7], [8]. For the case that the **PIP** is devoid of charge and the charge density is constant in the ink layer and only a static solution is considered we solve for Ez, the field in the ink perpendicular to the **PIP** surface. By convolving the charge density with a weighting function.

$$\alpha = 2\pi\sqrt{k^2 + m^2} \qquad (3)$$

$$Fwgt_{z=0} = \left(\varepsilon_i - \varepsilon_p \frac{\tanh(z_{ink}\alpha)}{\tanh(z_{ink}\alpha)} \right)^{-1} \quad (4)$$

$$Fwgt(1,1) = f(z_{ink}, Vd, \sigma, \rho, ...) \quad (5)$$

$$Fwgt_{z \neq 0} = Fwgt_{z=0} \frac{\cosh((z_{ink} - z)\alpha)}{\cosh(z_{ink}\alpha)} \quad (6)$$

$$E_z = FFT^{-1}(FFT(\sigma)Fwgt) \quad (7)$$

Where k and m are spatial frequencies, ε_i and ε_p dielectric constants, z is the coordinate perpendicular to the PIP surface and z=0 is the PIP ink interface, σ the latent image charge and ρ the ink charge density and Vd the developer voltage.

Phase Space Modeling

The models described above are solution of physical systems. The experimental inputs are, for example, the mass and developer voltage, the sensitivity of the **PIP** to light, the charge mobility in and on the **PIP** and the geometrical properties of the system and the laser light spot. The output of the models is a prediction of the shape of the ink mass which is transferred to the **PIP** and the electric fields which exist in the development region. For a single simulation we analyze a few quantities such as spot width, ink mass and possibly the cleaning electric field in a sensitive region (background). The simulations are repeated for a multi dimensional set of parameter ranges and the various quantities are mapped with the parameter ranges as coordinates. The following example relates to Figure 5.

In the HP-Indigo **LEP** press the electro-ink contains a space charge ρ, which changes according to parameters which we have only limited control over. ρ may vary between -140 to -60 C/m^3 from ink batch to ink batch and even in the same ink batch due to ink usage history. The fact is that we cannot easily measure the charge density in the development nip. In the HP-Indigo machine there is a routine named "Automatic Color Adjust" (**ACA**). The **ACA** changes the developer voltage (**Vd**) and the laser power (**LP**) until a printed solid patch displays the required measured Optical Density (**OD**) and until a certain gray scale patch has the required measured relative Dot Area (**DA**). This routine is used to stabilize the output of the press. It was empirically found that both **LP** and the **Vd** change the print. The **OD** of the solid patch is

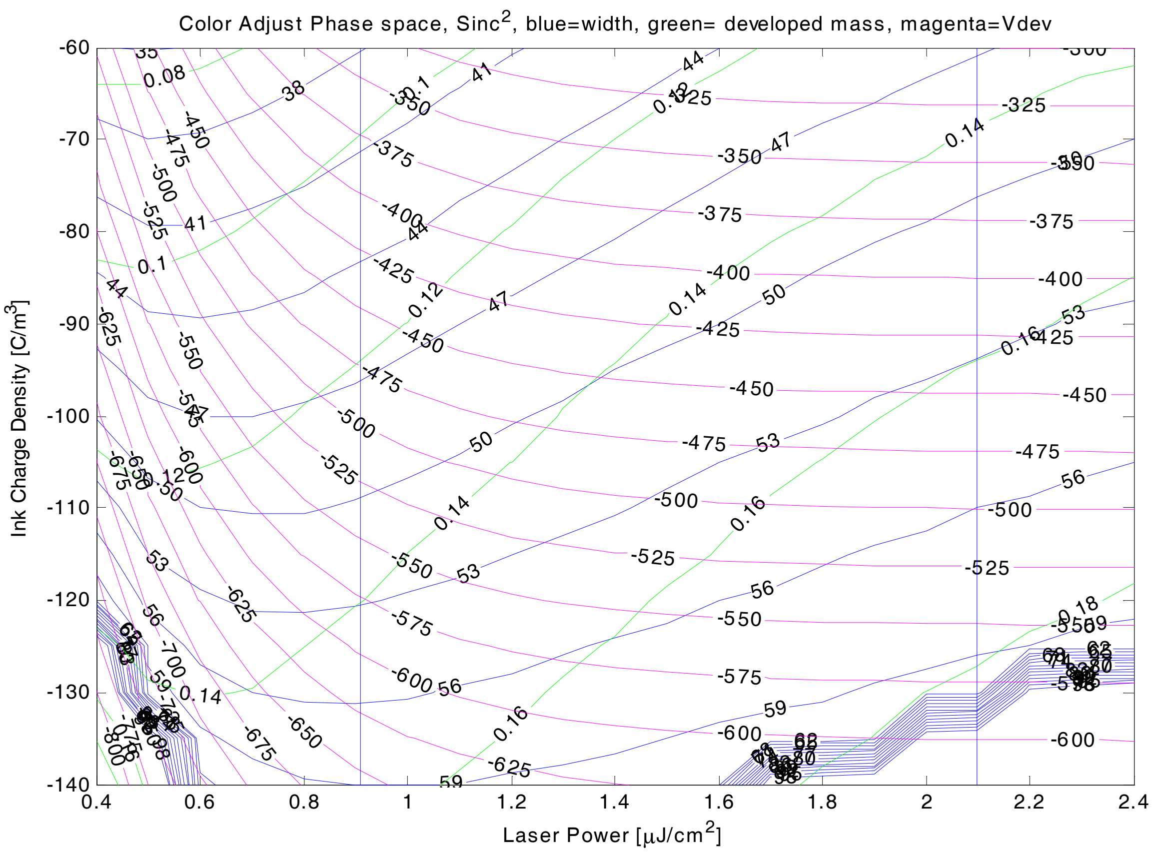

Figure 5 Phase space modeling for laser power and charge density

mostly affected by **Vd** and the spot size or grey scale patch **DA** affected by **LP**. The exact nature of the dependency was not known and thus a linear correction scheme is used. The contour plot map in Figure 5 displays the theoretical basis for the **ACA**. We solved the model for a single line performing a **PSM** by varying ρ and **LP**. The optical geometrical form is of $\text{sinc}^2(x)$ and resembles a horizontal line printed on an HP-Indigo press. The magenta curves are the calculated developer equi-voltage lines and define the required voltage to develop the required **OD** of a printed solid patch at said ρ and **LP**:

$$Vd = \frac{t}{PID}\left[\left(\frac{h\cdot\varepsilon_i}{\varepsilon_p}+t\right)\cdot\frac{\rho}{\varepsilon_i}\right]+V_l-\frac{\rho\cdot t^2}{2\varepsilon_i} \qquad (1)$$

Where ε_i and ε_p are the ink and **PC** dielectric constants, t the ink height, h the **PIP** height, V_l is the potential left on the PIP after solid illumination and PID>1 is the ink layer thickness on the developer relative to the ink layer thickness transferred to the **PIP.**

The diagonal blue lines are the calculated line width from the simulation and the green lines are the relative mass (developed ink mass divided by total ink mass). The vertical blue lines define the approximate region of laser power which is used. Experimentally we find that the mass defines the final size of the line on the print. Since the **ACA** attempts to keep the printed output constant we expect that it will keep a relation between **Vd** and **LP** following a line parallel to one of the green lines. Experimentally we found the trend to be similar and different from the previously used linear assumption.

This simple map shows a few interesting features. When we compare the green and the blue diagonals we can see that they are not parallel. This indicates that as we move in the machine phase space, as a result of ink variability and **ACA**, we change the aspect ratio of the original spots or lines. This may result in connection or cross talk between close elements for higher ρ or **Vd**. Another observable feature is the lower limit to line width. Notice to the left that the blue and green lines reach minima. On the bottom right part we see a pile-up of blue lines. When testing prints developed under similar high **Vd** conditions we find background development, or the appearance of ink where there should not be ink, especially between dense horizontal features. When looking at the low charge density region it seems that this region should result in fine features. Alas, this region is also described by weak electrical fields. Thus, in real life, printing under these conditions results in fragmented, unacceptable, fine features.

Conclusion

We have described the Indigo LEP printing engine and physical model used to predict the print result for varying physical development conditions. We further showed an example where we predict the variance of a simple feature, a line, under changing physical conditions. The multi-dimensional space defined by these physical conditions defines part of the phase space of the press. Understanding the different regions and expected variations we can control our system better. This is both in terms of controlling the variations as the press is printing, to attain the required stability, and the selection of where in phase space do we design our press to be so that the results will be with the required high quality.

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Author Biography

Dror Kella received his BSc degree in Physics and computer sciences from Tel-Aviv University, Israel (1987) and his PhD in physics from the Weizmann Institute of Science, Israel (1994). From 1994 to 1997 he worked at the University of Aarhus (Denmark) on molecular physics in storage rings. Then he moved to Applied Materials Israel where he designed Scanning Electron Microscopes. From 2002 he is working for HP-Indigo researching various aspects of the LEP process.