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Modeling Printing System Relationships based on Weibull Distribution

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Abstract

Commercial inkjet printing is a complex system that poses advanced technical challenges. The relationship between the amount of ink deposited per unit area and light reflected due to the ink in the same unit area is important to understand various imaging characteristics associated with a printing system. The amount of ink deposited per unit area is referred to as mass deposition. Optical Density (OD) defines the light reflected by ink on paper. Well-known methods used to define mass deposition versus OD require extensive knowledge of the halftone. These techniques require detailed halftone information regarding the mass deposition precisely for each halftone pattern as well as for the halftone calibration. Often, halftone information is unavailable, and this causes barriers in characterization of printing systems. With the advent of industrial printing, it has become necessary to characterize printers with media other than paper and unconventional ink options [1]. This must not be hindered due to lack of drop count information of the fluid/polymer based on the ink or the media. The model has been used over a wide range, from the microscopic level of printing lines and dots to the macroscopic scale of halftones. It describes printing systems having different halftone designs, resolutions, printer speeds, calibration, multipass and multidrop printing.

Introduction

In this paper, we demonstrate a flexible model that describes the optical density (OD) versus the ink mass deposition relationship of a printing system. The proposed model provides a relationship of OD as a function of the ink jetted onto the media, within unit area [2].

Traditionally characterization of printing systems involved determination of OD versus digital count (DC). This standard characterization is widely utilized to obtain the uncalibrated response of printer systems for the purposes of calibrating a print engine to a target response, such as linear OD. Combining the traditional measured OD versus DC with ink deposition versus DC, provides the required OD versus mass deposition data required for the proposed printer model. The resulting OD versus ink deposition relationship is independent of the printers halftone calibration. The paper demonstrates a method to obtain a regression model to the OD versus Deposition relationship, which further enhances its usefulness. This has wide applicability such as the predicting the amount of ink required to achieve a given OD and a measure of the amount of energy required to dry ink on any media.

Description

Figure 1 shows the flowchart which describes the basic steps required to obtain the proposed OD versus ink deposition relationship and its regression model.

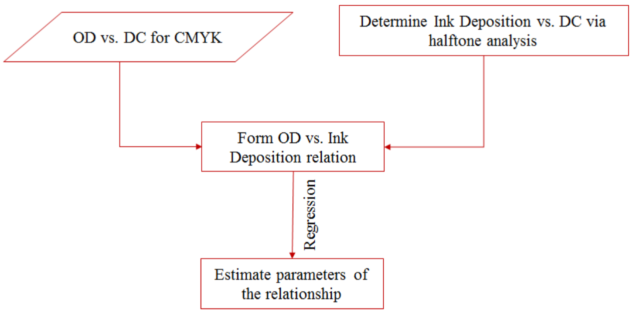

***Figure 1.** Determination of OD versus ink deposition relationship.*

The process of obtaining the OD versus ink deposition relationship is involved and requires us to first measure OD versus DC level for the each of the primary colors, using an uncalibrated halftone or equivalently employing an identity transfer function in the imaging path. This is followed by determination of ink deposition versus DC for the uncalibrated halftone which is used to print the samples to get OD versus DC as explained above. If a Multibit Threshold Array (MTA) point operation halftoning is used, this involves computing the total amount of ink for the the MTA at each digital count and dividing this amount of ink by the area of the threshold array. Ink volume or mass can be employed. This requires a detailed knowledge of the halftone design to understand the precise drop pattern for each level. Halftone analysis leads to computing the dot product of the number of drops of each size and the drop sizes and dividing the value by the threshold array area. Drop sizes must be measured through jetting experments. This provides a characterization of the amount of ink deposited within an area.

The next step involves forming the OD versus ink deposition relationship by combining the measured OD values with the halftone analysis. This is repeated for all data having the same gray level corresponding to the OD measurements to obtain the relationship over the entire tone range. Appling a regression model to the OD versus deposition data, we can determine the parameters of a model for the printing system. The described steps provide a basis for computing the proposed relationship. Before exploring the mathematical details of the proposed regression printer model, some basic properties of the model will be described.

This paper proposes using a Weibull model which is an adapted version of Weibull Cumulative Density Function [3] employed for reliability predictions. The proposal is based on experimental data described in section below.

It has been experimentally demonstrated that the superposition principle is applicable, i.e. the cumulative response from two or more ink sources is the same as the sum of the responses from each source individually. Therefore, the system has the characteristics of a linear system in the ink deposition domain. This property has been observed in several different ways. First, in multidrop printing system employing multibit halftones, where more than one drop size is present. Second superposition has been observed in multipass printing, where ink deposition is combined from two independent arrays of ink jet printheads to achieve higher OD. In both these cases, we observe that the model properly accounts for the combined ink deposition when predicting the resulting OD. The superposition property also permits addition of various ink contributions in the ink domain, converting the sum of the ink depositions to OD. This assumes summation of ink deposition on a large areal basis, however some evidence exists that the model also applies over small areas. It appears that the model describes a fundamental response of a printer system for a given ink set and paper. Determination of the respective models for different papers and CMYK ink sets, provides a means to characterize each combination.

Mathematical Model

The OD versus ink deposition relationship, which we will refer to as the ink model, provides a useful characterization of a printing system. A further improvement is to obtain a parametized model of this relationship. In this paper, a four parameter equation is used to obtain a regression model of the OD vs ink deposition relationship. The ink model is similar to the Weibull distribution used in Reliability Engineering to describe the Cumulative Distribution Function (CDF) . Classical Weibull distributions have two or three parameters, shape, scale, and location (or shift). The Weibull CDF model was adapted to describe a printing system by analyzing functional representations. The proposed equation also provides a closed form solution to the inverse relationship, allowing one to determine the ink deposition required to achieve a given OD.

In this paper, the simple model has experimentally been demonstrated to describe ink jet printing. Retaining the scale and shape parameters of the classical Weibull two parameter equation, paper white OD and maximum OD related parameters have been added. This produces a four parameter model as shown by the equation below,

$$\boldsymbol{OD} = \boldsymbol{p}(\mathbf{3}) \times \left(\mathbf{1} - \boldsymbol{e}^{\left(\frac{-x}{p(1)}\right)^{p(2)}}\right) + \boldsymbol{p}(\mathbf{4}) \qquad (1)$$

where, $\boldsymbol{p}(\mathbf{1})$ is the "Weibull" scale parameter, $\boldsymbol{p}(\mathbf{2})$ is the "Weibull" slope parameter, $\boldsymbol{p}(\mathbf{3})$ is the OD of the paper referenced OD. and $\boldsymbol{p}(\mathbf{4})$ is the OD of paper white. The OD values are therefore absolute, such as Status T. In addition, $\boldsymbol{p}(\mathbf{3}) + \boldsymbol{p}(\mathbf{4})$ is the maximum predicted absolute OD approaching infinite ink deposition.

Multiple exact solutions to the inverse solution exist. One of the inverse solutions can be described by equation 2 as shown below.

$$\mathbf{x} = \mathbf{e}^{\left(\ln\left(-\left(\frac{\ln(1-(\mathrm{OD}-\mathrm{p}(4)/\mathrm{p}(3)))}{\mathrm{p}(2)} + \ln \mathrm{p}(1)\right)\right)\right)} \qquad (2)$$

An imaginary value for the ink deposition $\boldsymbol{x}$ dicates that the desired OD is not achievable, since it exceeds the theoretical maximum $\boldsymbol{p}(\mathbf{3}) + \boldsymbol{p}(\mathbf{4})$. Of course, OD values less than $\boldsymbol{p}(\mathbf{4})$ are not possible, therefore the ink deposition should be clamped to zero ink deposition for this case.

A three-parameter model was also investigated, which essentially used a slope parameter equal to one. Overall it did not fit the experimental data as well as the proposed four parameter model.

Results and Discussion

Figure 2 illustrates a number of different experimental cases of multibit halftone designs for a single K plane ink and paper. OD versus ink mass deposition results are shown for 19 different experiments. These include halftone designs based on Direct Multibit Search [4] technology and an alternate algorithm Binary to Multibit (B2M) method. The printer resolutions are 720x360 DPI for the 64 meters per minute speed cases and 360x360 DPI for 128 meters per minute. The two different resolutions have different drop sizes. Dual pass results are shown for the results from 1) pass one (single set of printheads), 2) pass two (second identical set of printheads) and the 3) combined passes where the image is printed by the two different sets of printheads with the same image data. Note that the combined pass results have twice the ink deposition of a single pass. Cases for calibrated and uncalibrated are also shown. The range of cases plotted are very large. While there appears to be some variability between each case, the results in all cases show good correlation of OD to ink deposition.

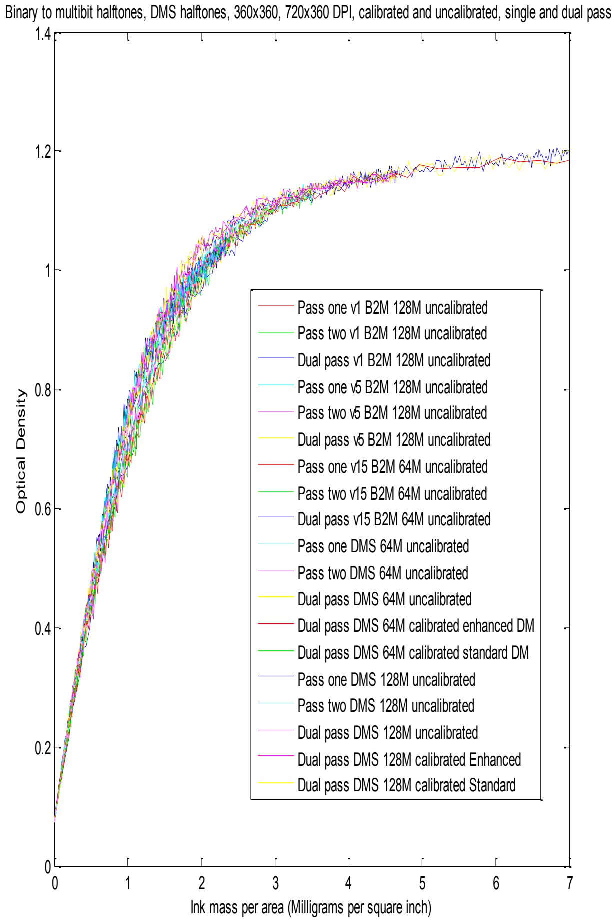

Figure 2. *Experimental results from 19 different experiments for a single K ink and paper.*

Figure 3 illustrates the process of obtaining the parameters of the Weibull based on measurements of OD and a detailed halftone analysis. Figure 3a demonstrates the measurements of OD versus different gray levels measured from printed patches. Based on a specific halftone design, the ink deposition for different drop sizes (considering a multibit halftone) at every DC is as shown in Figure 3b. Combining the information from 3a and

3b we get the Weibull plot illustrated in Figure 3c. This knowledge is used to derive parameters $\boldsymbol{p}(\mathbf{1}), \ldots, \boldsymbol{p}(\mathbf{4})$ of equation 1.

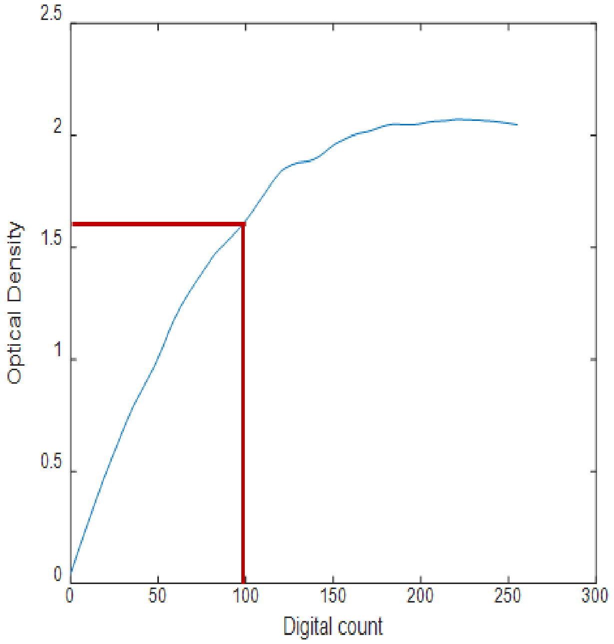

Figure 3a. *Conventional response for measured OD versus DC.*

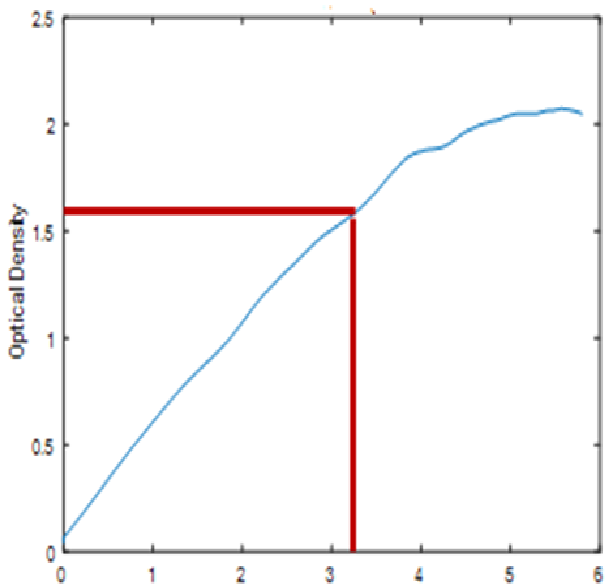

Figure 3b. *Ink deposition vs DC determined from halftone design and drop sizes. A multidrop system is illustrated where the ink deposition from small and large drops add to obtain the total deposition vs DC.*

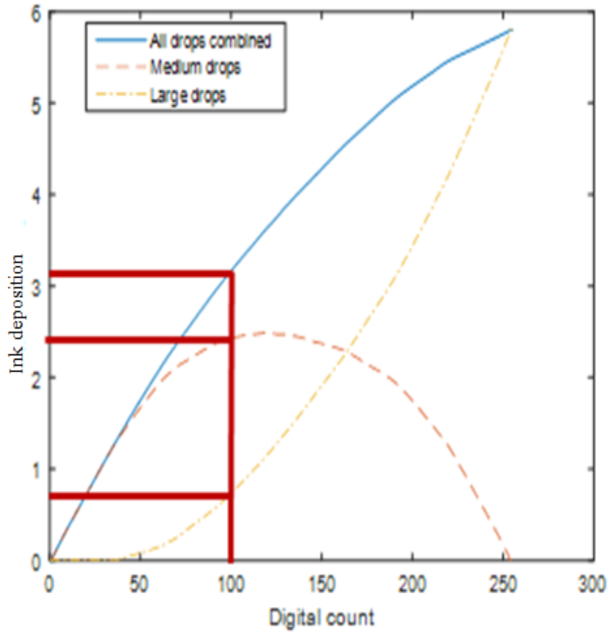

Figure 3c. *Data from the top two curves are combined to obtain the OD versus ink deposition.*

Conclusion and Future Work

The goal of this paper is to demonstrate a flexible model, which describes the OD versus ink deposition relationship of a printing system. This characterization of a printing system provides increased information beyond the traditional OD versus DC measurements. The model provides information for a single ink/paper set. A general four parameter model for the forward and inverse directions of this relationship has been provided which permit one to determine OD given ink deposition or ink deposition given OD. Data has been provided demonstrating sensitivity to factors such as multibit halftone drop size, halftone design, resolution and calibration. Further applications of this relationship are proposed which relate to ink drying. A very important application of the Weibull characterization of ink deposition versus OD is to provide a stable model for regression problems in machine learning as applied to printers. The proposed model has been actively used. Our experience is that it reliably provides a high corrected R squared, typically higher than 0.9. In addition, it results in small p values for the individual parameter regressions that are commonly much less than 0.05.

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Author Biography

Nikita Gurudath completed her bachelor's in engineering from Bangalore, India and obtained her Master's in electrical engineering at Ohio University, in 2014. Her thesis titled, "Diabetic Retinopathy Classification Using Gray Level Textural Contrast and Blood Vessel Edge Profile Map," is focussed on computer vision and pattern recognition for biomedical analysis. She is working at Ricoh, Boulder, Colorado since January 2015 as an Imaging Science Engineer.

Mikel Stanich is a Senior Technical Staff Member and Master Inventor working for Ricoh in Boulder, Colorado, focused on issues related to Imaging Science. He is currently a fourteenth plateau level inventor who was awarded a "Distinguished Patent Award" (DPA) in Feb. 2015 for a key patent that covers a non-integer scaling method.

Larry Ernst earned his BSEE from University of South Carolina in 1968 and his MSEE from University of Kentucky in 1972. During the early stages of his career, he was involved developing and designing electrophotography copier and printer products. As the printing industry continued to demand higher image quality, he focused on image quality and researched alternative printing technologies. In 2005, he was appointed an IBM Fellow for leadership in the strategic directions and implementation of critical print and image quality technologies. After retiring from IBM, he joined Ricoh Americas Corporation as a Ricoh Fellow continuing to focus printer strategic directions and implementation of critical print and image quality technologies. He is either the invertor or a co-inventor on more than 55 issued US patents and numerous issued patents worldwide.