Automated Test Equipment for the Development of Media for Digital Printing

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Abstract

Rapid advances in electrophotography and inkjet printing are imposing greater demands on requirements for paper performance. Paper requirements are generally classed as runnability, printability and usability. These terms refer, respectively, to the ability of the paper to be transported smoothly through the print engine; the ability of the media, interacting with the marking material, to produce an image of the desired quality; and a variety of other characteristics such as overall look and feel, freedom from curl, cockle and bleed-through, image permanence, and readiness for finishing operations such as folding, creasing and binding. This paper focuses on printability in electrophotography and inkjet printing. We discuss several testing and measurement methodologies and their underlying measurement principles, including techniques for measuring and mapping dielectric relaxation in paper, quantitatively determining fusing latitude, and analyzing print quality. The efficacy of these methodologies is demonstrated by practical examples.

Introduction

The rapid development of electrophotography and inkjet printing imposes increasing demands on the requirements for paper. Requirements for papers used in digital printing fall into three categories — runnability, printability and usability. Runn*ability* refers to the ability of the paper to be transported successfully through the print engine without jamming, breaking, misfeeding or misregistration. Print*ability* refers to the ability of the paper to receive the marking materials, such as toner or ink, and provide a clear, legible, aesthetically pleasing and defect-free image. The term us*ability* encompasses qualities such as "look and feel," absence of curl and cockle, absence of bleed-through, image permanence (lightfastness, waterfastness and abrasion resistance), and readiness for finishing operations such as folding, creasing and binding. To attain the "*-ability*" level demanded, advances in techniques for measuring paper properties are needed both off and on the paper machine, in the research laboratory, and on the production floor. In this paper, we will focus on testing and measurement technologies addressing printability, particularly in electrophotography and inkjet printing. Selected methods and their underlying measurement principles are described, including: 1) measuring and mapping dielectric relaxation in paper; 2) quantitative determination of fusing latitude; and 3) objective print quality analysis. The first two methods are critical to achieving high printability in electrophotography, and the third method is central to product development and process control in all digital printing technologies. The efficacy of these methods is demonstrated by examples of practical applications.

Printability Requirements in Electrophotography

In electrophotography, the two processes affected by paper properties are the *transfer* and *fusing* of toner to the paper.

In toner *transfer*, a corona or roller charger is used to produce an electric field in the paper, attracting the toner from the photoreceptor onto the paper surface. The electrical behavior of the paper clearly plays an important role in the efficiency and quality of this process.[1-2] Many specialized instruments are available for measuring the electrical properties of paper; however, it is sometimes difficult to establish a clear relationship between the quantity measured and the ultimate performance of the paper.[1] Difficulties arise for several reasons: 1) the electrical properties of paper are very moisture sensitive, a fact that contributes to measurement variability and points to the need for careful control during measurement; 2) the contact conditions can greatly affect the measurement; and 3) many measurement techniques are based on the assumption that the electrical behavior of paper is ohmic – in most cases not an accurate model of the dielectric relaxation process in a semi-insulating material such as paper. In semi-insulating materials, dielectric relaxation is usually a very complex process involving charge injection, generation, transport and trapping[3]. Hence, in developing a technique for measuring the electrical properties of paper involved in the transfer process, we must consider the physics of the process and apply a technique that best simulates the process conditions in actual practice. Another important consideration in measuring electrical properties of paper as they relate to toner transfer is that the properties of paper are not uniform in the sheet – a characteristic referred to as the "formation" of the paper. Since paper is made of cellulose fibers distributed quasi-randomly, non-uniformity in the distribution of the fibers often exists in the plane of the sheet, with a spatial scale on the order of 1 to 5 mm. Not surprisingly, paper formation can affect the uniformity of toner transfer and the quality of the resulting image.[4] To properly characterize the electrical properties of paper as they relate to toner transfer, it is therefore desirable to examine the spatial uniformity of the paper formation, which can be done by mapping dielectric relaxation.

In electrophotography, the predominant technique for fusing toner to paper is hot-roll fusing. In this process, fixing the toner powder to the paper involves liquification, coalescence or sintering, spreading, penetration into capillaries, and resolidification[5]. In addition to toner fixing, a print quality characteristic of major importance to the end-user is gloss. The degree of both fixing and gloss is determined by a variety of factors. These include the interactive effects of process variables such as time, temperature, pressure, and lubrication. Materials variables are likewise critical. These include toner resin rheology, toner softening and melting temperatures, fuser and pressure roller elasticity, surface energy of the fuser roller and the paper, wetting and adhesion characteristics of the toner, and heat transfer characteristics of the paper. The heat transfer properties of the paper include bulk conductivity, specific heat, and thermal contact resistance. The caliper (thickness) of the paper has been shown to be critical to fusing quality when the residence time of the paper in the nip of the rollers is shorter than the thermal diffusion time (determined by the caliper)[6]. The coating on the paper is yet another factor affecting print quality. Gloss, for example, and in particular "differential" gloss, is affected by the nature of this coating[7].

Printability Requirements in Inkjet Printing

It is now well known that print quality in inkjet printing is mainly determined by the interaction of the ink and the media[8-9] and by the shape, size and uniformity of fundamental image elements such as dots and lines.[10] The basic mechanisms that determine the shape and size of dots on the media include the absorption and spreading of ink drops, the interactions between drops, the evaporation of the carrier in solvent-based inks, the solidification of hot-melt ink drops, and the curing of UV-cured inks after the drop strikes the media. From a research and development point of view, testing and measurement requirements for ink-media interactions can be broken down into two categories, namely, dynamic and static measurements. Dynamic measurements examine the time-dependent phenomena of absorption and spreading of single drops and the interaction and coalescence of multiple drops. Static measurements examine the details of the image on the media to assess the quality of the results of the ink-media interaction – a technique called print quality analysis. Print quality can be evaluated visually and subjectively by human observers, or it can by analyzed objectively by computerized techniques. Although subjective print quality analysis is vital for capturing end-user preferences, a computerized image analysis system, and preferably an automated system configured specifically for print quality analysis, is critical for providing the quantitative information needed for research, product development and production quality control.

Measuring and Mapping Dielectric Relaxation of Paper

The electrical properties of paper are usually discussed in the literature in terms of resistivity and static charge dissipation behavior. ASTM standards exist for measuring volume and surface resistivities (ASTM D4949-89)[11]. The KCL method[12] and the Kawaguchi paper analyzer have reportedly been used to analyze the static charge dissipation behavior of paper. However, all these methods have shortcomings. For example, the ASTM standard uses contact electrodes, which means that the consistency of the measurements depends on the consistency of experimental variables such as the contact pressure between the electrodes and the paper. Furthermore, one may question the applicability of the contact measurement method in electrophotography since the charge injection process used in this method must be quite different from the injection process used in corona charging. In the KCL and Kawaguchi methods, although the basic measurement principle resembles reasonably well the actual static charge dissipation in the electrophotographic application, the data analysis is over-simplified in that only the maximum voltage and "half-life" are typically reported. While these measurements are useful, they can lead to inaccurate conclusions since they provide information on only one aspect of the total time-dependent dielectric relaxation behavior of paper. In the toner transfer process, dielectric relaxation in the paper subsequent to corona charging is usually non-ohmic and cannot be described by an exponential RC-type model. The process is a complex combination of charge injection, generation, transport and trapping. To accurately characterize such a process, it is best to simulate it as closely as possible in the measurement methodology, which in this case means corona-charging the paper and then monitoring its surface potential decay. This technique is similar to the Electrostatic Charge Decay (ECD) technique reported previously in the literature.[13-14] In the computer-controlled ECD technique, the sample-under-test is corona charged and the subsequent surface potential decay is monitored to depict the dielectric relaxation characteristics of the sample, or simply to reveal the presence (or absence) of bulk or surface defects. Figure 1 illustrates a basic system configuration for the ECD measurement technique. A novel feature of this technique is that a 2-D map can be generated revealing the dielectric relaxation characteristics of the entire sample. Such a map is a powerful tool for studying these characteristics.

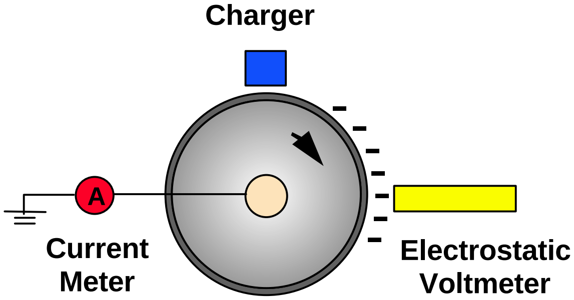


Figure 1: Basic System Configuration for ECD Measurements

Residual Voltage Mapping

Figure 2 illustrates surface potential decay measurements on an electrophotographic grade paper at three humidity levels: <20%, 50% and 90%. The initial voltage on the sample was approximately 700 volts. As shown, the surface potential decay rate increases significantly as the humidity level increases: at 1 second, the ECD voltage is 280, 23 and 1 volt at <20%, 50% and 90% RH, respectively, corresponding to paper moisture levels of <3%, 6% and 12%[15].

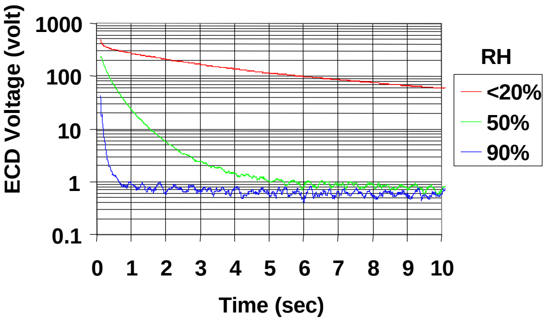


Figure 2: Surface Potential Decay in an Electrophotographic Paper at Different Humidity Levels

Figure 3 is a surface potential map of a similar electrophotographic grade paper at approximately 50% humidity. The map was obtained by means of an ECD computer-controlled scanner.[16] From this map, two important observations can be made: 1) the variation in residual voltage is rather substantial — from less than 250 volts at some locations to more than 450 volts in others; and 2) the spatial variation in residual voltage has a characteristic wavelength of approximately 1 to 5 mm, which is of the same order of magnitude as the formation, i.e., the spatial variation in the distribution of the cellulose fibers in the paper.

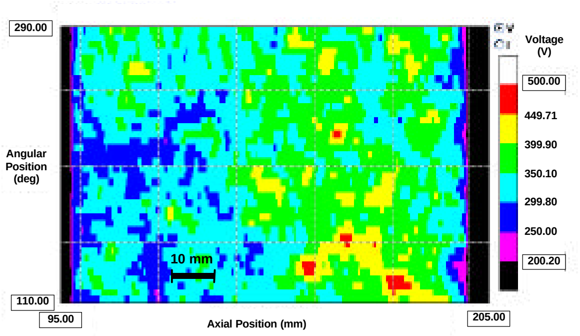


Figure 3: Surface Potential Map of an Electrophotographic Paper at approximately 50% RH

The practical usefulness of the ECD technique for measuring the dielectric relaxation characteristics of paper can be summarized as follows:

1) The ECD method is a nondestructive, non-contact technique closely simulating the corona charging that takes place in the toner transfer process in electrophotography. The dielectric relaxation characteristics of paper can be determined conveniently by this method.
2) Because the measurement technique closely simulates the actual transfer process, we can postulate that the electrical parameters (such as charge injection and trapping) estimated by this technique are meaningful for predicting transfer efficiency.
3) The ECD technique offers a novel mapping approach for characterizing the non-uniformity in the paper. It would be interesting and potentially very useful to establish correlations between electrical, microstructural and print quality uniformity.

Quantitative Determination of Toner Fusing Latitude

Achieving a broad latitude in toner fusing is important for ensuring high print quality despite uncontrollable variability in fusing conditions. In previous publications[6,17], we have demonstrated the ability of a commercially available toner fusing test apparatus to determine fusing latitude. A schematic of the system is shown in Figure 4. Using this apparatus in two series of experiments, we were able to demonstrate the effect of paper on fusing quality.

In the first series of experiments[6], we showed that increasing the caliper of the paper degraded fixing quality (a measure of fusing quality) if the thermal diffusion time through the thickness of the paper was less than the residence time of the paper in the nip of the fuser rollers. In the example shown in Figure 5, the thermal diffusion time was computed from equation 1 to be greater than 70 msec for a media thickness of more than 200 µm; and based on an independent measurement of the nip width, the residence time in the nip was estimated to be 820 msec and 180 msec at 2 ppm and 10 ppm, respectively. At 2 ppm, since the residence time is significantly longer than the thermal diffusion time, the paper thickness has no effect on the degree of fix. At 10 ppm, on the other hand, the residence time is comparable to or shorter than the thermal diffusion time, and an increasingly significant thickness effect on the degree of fix was observed.

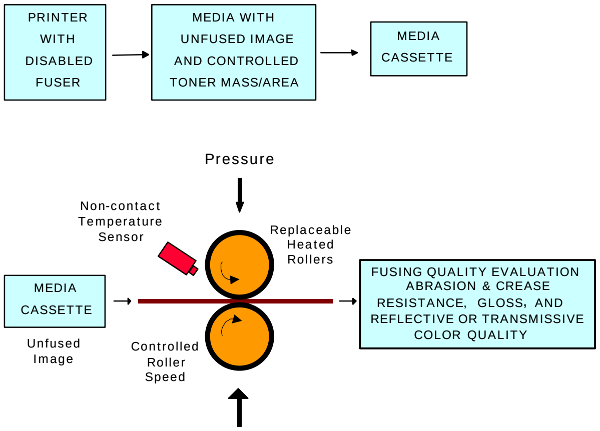


Figure 4: Schematic Diagram of a Computerized Toner Fusing Test Apparatus

In the second series of experiments[7], the gloss of a coated paper was measured as a function of fusing temperature and toner coverage. It was found that gloss is a monotonically increasing function of fusing temperature (Figure 6).

However, gloss is also a function of toner coverage. On a gray scale from 0% gray (white) to 100% gray (black), gloss decreases at the lower end of the scale (0% to about 45% in Figure 7) and then increases as toner coverage increases. The increase in gloss with fusing temperature can be explained simply as enhanced specular reflection due to melting and smoothing of the toner particles as fusing temperature increases. On the other hand, at any specific fusing temperature, toner coverage at the lower end of the gray scale causes a decrease in gloss because at this stage measurable gloss is determined primarily by the gloss of the coating on the paper. As a result, increasing toner coverage simply reduces optical reflectance and hence the amount of gloss. However, as toner coverage continues to increase, the melted, smoothed toner layer begins to build a specularly reflective surface, leading to a higher and higher gloss value as the toner coverage increases. Combining the two mechanisms — that is, decreased gloss at low toner coverage due to reduced reflectance of the paper coating, and increased gloss at high toner coverage due to the smoothed toner layer itself — one would expect to see a gloss curve with a saddle, as illustrated in Figure 7. Since the two mechanisms are in competition, it is not surprising that the location of the saddle depends on the fusing temperature.

$$t = \frac{d^2}{a} \qquad [1]$$

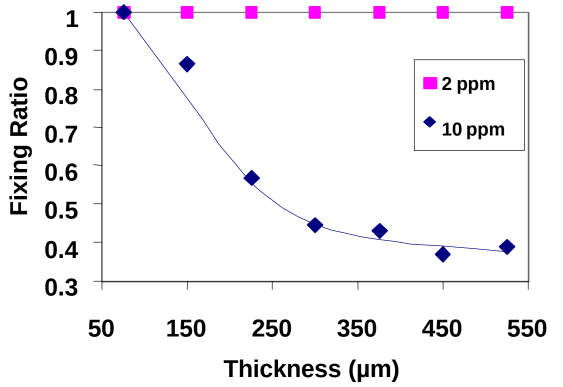


Figure 5: Effect of Paper Thickness on Fusing Quality at Two Fusing Speeds

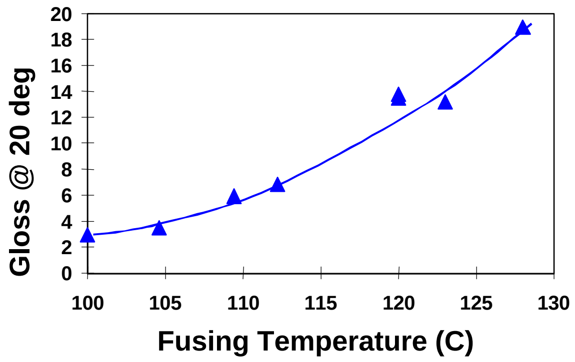


Figure 6: Effect of Fusing Temperature on Gloss at 100% Gray Toner Coverage

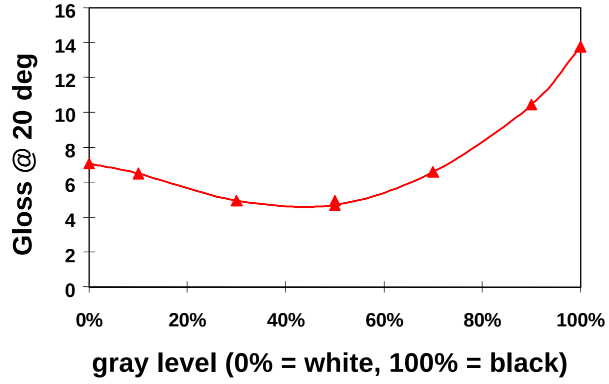


Figure 7: Effect of Toner Coverage on Gloss in Coated Paper at a Fusing Temperature of 125 C

The experiments described above demonstrate the effectiveness of the computerized toner fusing test system in performing parametric studies. With this apparatus, a researcher can concentrate on designing experiments and analyzing results rather than on such things as setting up the apparatus. In short, this test system offers significant improvements in the efficiency with which experiments can be conducted, producing substantial gains in R&D productivity.

Automated Print Quality Analysis

Since the ultimate objective in any digital printing technology is to deliver the desired level of print quality to the end-user, it is essential to track progress in R&D in terms of improvements in print quality. To track these improvements and gauge advances relative to target requirements, one must have objective means of evaluation. An objective print quality analysis system is essentially a computerized machine vision system equipped with analytical software specifically designed to make quantitative assessments of the basic image quality elements – dots, lines and solid areas. In addition to quantitative analysis capabilities, such a system must use well-designed software that is analytically sophisticated yet easy to use to afford meaningful enhancements in productivity. The hardware architecture of a commercially available, automated print quality analysis system is shown in Figure 8. The system uses a CCD camera to acquire high resolution images (5 to 10 μm per pixel) for analysis. It uses Microsoft Excel-based control software to provide highly sophisticated analysis functions for image quality. The system can be operated either in automated mode in production environments, or interactively in R&D environments. Table 1 contains a list of basic image elements for which the system provides analysis functions. This list represents the essential, and minimal, print quality metrics required in systems of this kind. More advanced features should also be incorporated to enhance the utility of the system. Advanced and application-specific capabilities may include: automated image location, transparency characterization, barcode readability analysis, analysis of digitally-printed textiles, and quality control of inkjet print heads in production, among others.

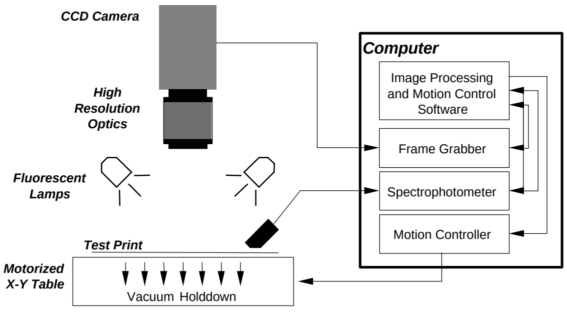
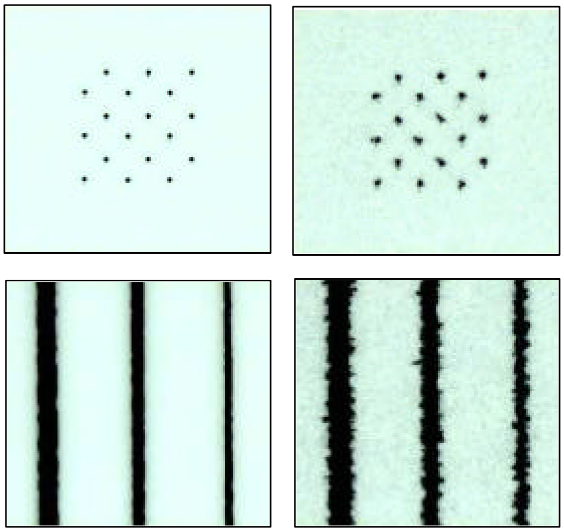


Figure 8: Hardware Architecture of an Automated Print Quality Analysis System

The automated print quality analysis system described has many applications. One example is print quality analysis on inkjet media[10]. In optimizing inkjet media, one essential task is to control the shape, size and uniformity of the dots created by each ink droplet. If the media is designed properly, the dots should be round, with little dot gain and a high level of uniformity among dots. To illustrate this, Figure 9 shows a composite of dots and lines printed by the same inkjet printer on two different paper types: a glossy, coated paper and an uncoated paper. From this figure, it is clear that dot quality is the essential building block that determines the quality of more complex geometric elements such as lines and solid areas. Using the roughness of the paper, or media noise, as the control variable, critical image quality metrics such as modulation, tone reproduction and color gamut are all shown to be affected by the media type in a very predictable way (Figues 10-12): As media noise increases, modulation (resolution), tone reproduction and color gamut decrease.

Table 1: The Basic Print Quality Attributes

Image Element	Quality Attribute
Dot	▪ **Dot location** ▪ **Dot gain** ▪ **Dot shape** ▪ **Edge raggedness** ▪ **Satellites**
Line	▪ **Line width** ▪ **Edge sharpness** ▪ **Edge raggedness** ▪ **Optical density** ▪ **Resolution (modulation)**
Solid area	▪ **Optical density (tone reproduction)** ▪ **Color (chroma, hue)** ▪ **Noise (graininess, mottle, background, ghosting** ▪ **Gloss**



Glossy, coated *Uncoated*

Figure 9: Good Print Quality Begins with Well-controlled Dot Shape, Size and Uniformity

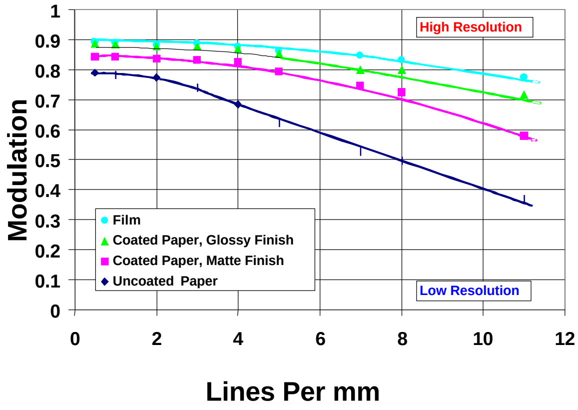


Figure 10: Effect of Media Type on Modulation (Resolution)

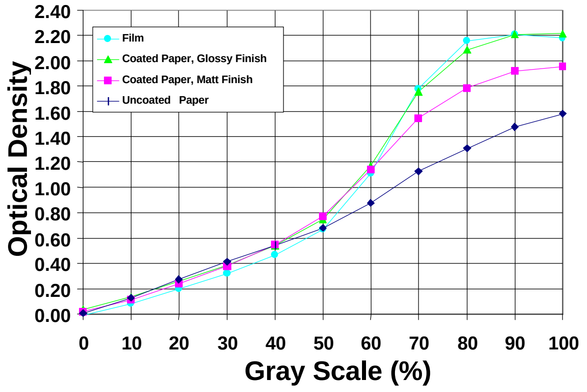


Figure 11: Effect of Media Type on Tone Reproduction

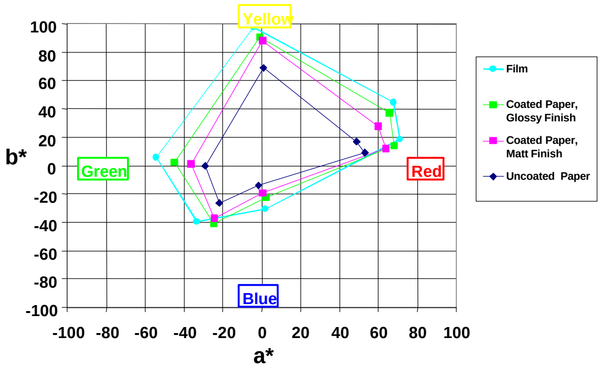


Figure 12: Effect of Media Type on Color Gamut

The same study also demonstrated that objectively measured print quality can be correlated with subjective assessments. This substantiates the validity of the automated methodology described.

Summary

Although the papermaking industry is highly sophisticated in its use of sensor applications and on-line process control, rapid advances in digital printing have imposed unprecedented demands for new measurement technologies for both on-line and off-line media characterization. This paper highlights the need for new measurement methodologies for use in developing digital printing media and demonstrates how three examples of advanced instrumentation respond to this need. The computer-controlled methodologies discussed are a novel mapping technique for dielectric relaxation of paper, a test apparatus for determining fusing latitude in hot-roll toner fusing, and an image analysis system for objective print quality evaluation.

The dielectric relaxation mapping (ECD) technique avoids the weaknesses of other approaches for predicting toner transfer efficiency. It provides a powerful tool for paper manufacturers and for electrophotography in general for understanding critical paper properties, particularly in light of the non-uniformity inherent in most paper structures. This approach to quantifying paper formation directly impacts ultimate print quality with respect to image non-uniformity and mottle.

The fusing latitude in hot-roll fusing is a determining factor in the ultimate quality of electrophotographic prints, but predicting fusing latitude and fusing quality has been a daunting task. A test system is introduced that makes possible highly effective parametric studies of toner fusing and provides a means for efficient, productive and quantitative R&D.

These two examples bring into focus the principle that test methodologies for digital printing should be designed to simulate the actual printing technology under investigation. The use of a corona charging method in dielectric relaxation measurement eliminates uncertainty arising from conventional measurement techniques involving contact electrodes. The toner fusing test apparatus simulates the electrophotographic fusing subsystem, allowing for clear and unambiguous interpretation of test results.

The importance of objective, quantitative print quality analysis cannot be over-stated. While the basic idea of using a CCD camera or a flatbed scanner to capture a printed image for analysis may now seem obvious, less obvious is the careful consideration that must be exercised in designing the system to ensure accurate and reproducible results. Moreover, to fully exploit the potential of such a system, good software design iscritical. In practical terms, it is the software design that is the real differentiator between a truly powerful system and a less powerful one.

Clearly, these are just a few of the kinds of test systems needed. A whole new generation of test systems remains to be developed. As our understanding of the requirements and the underlying physics of digital printing improves over time, innovative approaches to measurement and control in media technology will soon parallel the rapid advances in digital printing technologies.

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