Automated Print Quality Analysis for Digital Printing Technologies

Ming-Kai Tse, David J. Forrest and John C. Briggs
QEA, Inc.
99 South Bedford Street #4, Burlington, MA 01803 USA
Tel: (781) 221-0080 · Fax: (781) 221-7107
e-mail: info@qea.com
URL: www.qea.com

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QEA, Inc.
Burlington, Massachusetts, USA

Abstract

Automated print quality analysis systems are evolving to new levels of functionality, integration, and productivity and are becoming critical to the advancement of digital printing technology. As tools for communication within the industry, these systems can help to achieve a needed consensus on print quality standards and the procedures for quantifying them. In this paper we will describe in some detail the design of an automated print quality analysis system, discussing our design choices and the rationale behind them. The system analyzes prints on any media produced by any printing technology. To demonstrate a representative application of the system, we will present results of a case study in which automated print quality analysis was applied to inkjet printing. User requirements and key criteria for evaluating a system of this kind will also be discussed.

Introduction

Evaluating print quality is commonly done by panels of judges surveying samples and rating them according to preference. End-user preferences are central to the design of products, and subjective methods will always play a significant role in the development of products for digital printing technologies. However, subjective print quality evaluation has decided shortcomings. Human vision, though impressive in its ability to detect and characterize detail, is nevertheless inconsistent and personal. Furthermore, the results of subjective print quality assessments are collections of adjectives, and we are all too aware of the imprecision of descriptive terms and the difficulty of knowing exactly how to interpret them. Thus, while subjective evaluation may convey a sense of the end-user's tastes and requirements, its qualitative nature and poor reproducibility limit its applicability, particularly in R&D and production quality control. In these applications, quantitative analysis is essential for product and process evaluation, problem solving and failure analysis. Therefore, we must be able to "turn adjectives into numbers!" with objective tools — in this case, with an automated print quality analysis system.

State-of-the-art print quality analysis in particular is essentially a computerized machine vision system configured to measure those factors that specifically affect print quality. Typically with these systems, a specially-designed test target is automatically scanned, and specified features within the field of view are analyzed to obtain numerical values for specified quality metrics. The test target usually consists of basic image elements such as dots, lines, and solid areas carefully arranged to highlight specific print quality attributes relevant to the application. An automated print quality analysis system of this kind eliminates uncertainties and inefficiencies inherent in subjective evaluation.

The principles of automated print quality analysis are built on the understanding that even the most complex images, such as digital photographs, are made up of basic elements. Analyzing these basic elements — dots, lines and solid areas — is a fundamental task of quantitative analysis. Beyond this, however, an automated print quality system requires features and functions that go much further, to make it a practical tool, particularly where specific image attributes are known to have critical importance in particular applications. For example, dot location and dot size are critical to inkjet print quality; therefore, a well-designed analysis system should incorporate high level functions for efficiently characterizing these parameters. Line edge quality and optical density are key determinants of barcode readability; therefore, specialized quality metrics targeting these attributes should be provided. For production applications, efficiency and performance consistency are key requirements; automated on-line calibrations are therefore essential. In brief, a well-designed automated print quality analysis system must provide a comprehensive set of tools, including a full range of image and print quality metrics. The value to the user is significantly enhanced if application-specific metrics and features are also incorporated. This paper will describe the methodology underlying the design of a practical, commercially-available test system to meet the diverse requirements of product development for digital printing.

User Requirements

Automated print quality analysis serves all levels of decision making in product definition, development and delivery. It is a tool for unambiguous communication both within organizations and between organizations in the digital printing industry. In marketing, for example, quantitative print quality analysis is used in competitive benchmarking and product positioning. In research and development, the ability to make repeatable, quantitative measurements is essential for gaining new insight, and provides a yardstick for product and process improvements. In production, automated print quality analysis ensures efficient measurements and eliminates the problem of operator dependence – a major issue in manufacturing environments. For these reasons, automated print quality analysis is expected to provide the basis for industry-wide quality standards.

For the potential of an automated print quality analysis system to be realized, it must offer unmistakable advantages to the user. In our experience, the following requirements provide a guide for designing such a system.

Ease of Use

An automated print quality analysis system is likely to be used not only by trained engineers but also by less experienced operators. Therefore, operator-friendliness is a key requirement. To satisfy this requirement, the system should use a software platform and a well-designed graphical user interface that are already familiar to the majority of users — for example, Windows® 95 running a well-known application program such as Excel. The advantage of this implementation is that not only are most users already familiar with the look and feel of Excel, but Excel places many highly developed analytical, programming, and reporting tools at the user's fingertips, greatly enhancing the functionality of the system.

Integration of Multiple Test Functions

In addition to providing quantitative information, an important objective in designing an automated print quality analysis system is to integrate the many test functions that previously had to be performed independently. These were time consuming and invited operator error. A well-designed test system integrates a multitude of measurements including dimensional analysis (such as dot gain and line width), optical density measurements (for tone reproduction studies), color analysis (e.g., CIELab color measurement) and gloss evaluation. Such integration streamlines test functions and greatly enhances productivity.

Expandability and Flexibility

Digital printing technology is continuously changing and its applications are rapidly growing. For this reason, the requirements for an automated print quality analysis system are sure to evolve over time. Therefore, it is imperative that the system be highly expandable, both in its software and hardware configurations. Similarly, since these systems are likely to be used for multiple purposes, they should be designed for the greatest flexibility to ensure that they can accommodate the diverse range of users' objectives. In the case of an R&D user, for example, interactivity and detail are key, whereas in a production line, automation and short cycle time are the main issues.

Consistent Performance

A print quality analysis system is an analytical instrument, and users must be able to have complete confidence in the validity of its results. The ability to deliver consistent and reproducible measurements is a fundamental requirement, and the system must therefore incorporate tools and procedures for routine — and preferably automated — calibration of its performance.

Available Systems

Many print quality (often called image quality) analysis systems have been reported in the literature[1-9]. Most of these systems, however, are proprietary or laboratory systems not designed for general-purpose, routine use in development and production environments. Very few systems specifically dedicated to print quality analysis are as yet commercially available. Commercial implementations must respond to user requirements as outlined above to achieve the highest level of customer satisfaction. The implementation described below is an example of such a system.

Design of a High Performance Automated PQ System

Hardware Architecture

The hardware for print quality analysis can be deceptively simple in appearance, as illustrated in Figure 1.

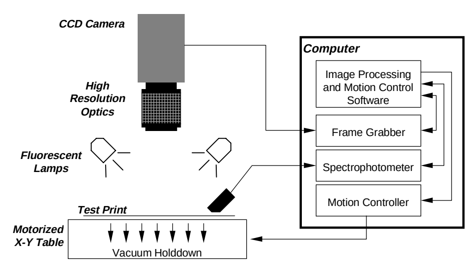

Figure 1 Print Quality Analysis System Hardware Architecture

The success of a system of this kind depends how well the design meets the goals of automation and integration. For example, selecting an x-y table is easy; but making it useful depends on being able to develop simple means of holding down the test sample and of making the lighting on the sample uniform even as the table moves. The print quality system should perform as a productivity tool, and this means automation. Much can be determined about print quality with a densitometer, pencil, paper, and the services of a technician. But when many samples need to be measured and many different measures of print quality need to be made, traditional labor-intensive measurement tools are simply impractical. The automated print quality system hardware makes measurements fast, which means that a high volume of samples can be analyzed in a short time.

The hardware for print quality measurement includes a number of subsystems, as follows.

Image Capture and Digitization

A fundamental step in measuring print quality is acquiring a digital image of the area to be analyzed. Digital images are most commonly obtained by using scanners and 2-dimensional CCD (charge coupled device) cameras.

Scanners are made from 1-D CCD elements on a motorized stage. The primary benefits of scanners are their low cost and their ability to image large areas (e.g., a full A4 page) in a single pass. Scanners are well suited to measuring print quality issues such as print skew and density uniformity. However, scanners are not as well suited to making measurements of fine features, such as small dots and fine width lines. While high-resolution scanners are available, they are expensive and generate large files that can be difficult to work with. So while scanners can play an important role in print quality analysis, currently 2-D CCD cameras are generally preferred.

A 2-D CCD camera coupled with high magnification optics provides a quick means of imaging a portion of a printed sample for analysis. Cameras are available in a wide range of resolutions, 1024x1024 or 640x480 pixels being perhaps the best suited to PQ analysis. Considerations in choosing one camera over another include image size, field of view, file size, and cost. There is a natural tendency to think that higher resolution is better, but processing of mega-pixel images can significantly reduce throughput on Pentium class PCs. Generally, a 640x480-pixel camera set to a magnification of about 10 µm/pixel provides a good compromise between field of view, resolution, file-size, and cost. Adjustable optics allows the user to easily change the magnification for different applications.

Hardware needed for acquiring an image includes a frame grabber for the camera. The selection is generally governed by the choice of camera, the computer, and the available driver software.

Illumination Source and Diffuse Lighting Environment

Lighting is perhaps the most overlooked and least understood aspect of measuring print quality. Lighting must be consistent over time and uniform across the camera's field of view. If it is not, measurements of certain attributes (e.g., optical density) will not be accurate.

Key to good illumination is a light-tight scanning enclosure, which eliminates several sources of measurement error. The enclosure excludes ambient light, so that changes in room lighting will not effect the measurements. The enclosure also eliminates any shadows cast by the equipment operator, which could otherwise be a source of measurement variability.

For uniform lighting, diffuse lighting is required. Typical high intensity sources such as fiber optic bundles and ring lights are not well suited to this purpose. More appropriate for PQ measurements are multiple light sources mounted at a carefully selected distance from the print sample. With this arrangement, light bounces off the interior of the enclosure (typically painted white), producing uniform lighting in the field of view of the camera. Appropriate light sources might be two to four cool white fluorescent light bulbs.

Alternative light sources may be necessary for specific applications. For example, special lighting is needed for transparencies, spectrophotometry, gloss, and surface texture measurements.

Motion Control

To be able to make PQ measurements over the entire surface of a printed page, the system must have an x-y motion stage. The motion stage must be flat, fast, and accurate. Flatness is required so the camera remains in focus over the entire surface of the printed sample. The degree of flatness required is in part determined by the depth of focus of the camera, but typically it is on the order of 25µm flatness.

Speed requirements are application dependent, but most moves should require no more than a few seconds to complete.

Accuracy requirements for x-y positioning are also application dependent. If all print quality measurements are to be made within a single field of view, relatively coarse motion control (e.g., 100µm accuracy) is quite adequate. In our experience, this is typical of most PQ applications. In cases where PQ measurements need to be made in successive fields of view, greater accuracy is needed. For example, measuring the distance between two lines 100 mm apart may necessitate knowing the precise location of the motion stage (e.g., 5µm accuracy), in which case optical encoders are typically used.

For convenience, a Z-axis adjustment should be provided to focus the camera.

Media Handling

A method is required for holding the test sample flat on the x-y table so that the lighting is consistent and the sample is in good focus. Adhesive tape is probably the simplest method, but it is not always convenient or effective. Another common method is a glass plate. This can be used for samples of almost any size, but drawbacks are that it makes contact with the sample and that it can quickly become dirty. Another concern with glass is that since the sample is viewed through it, PQ measurements may be affected. In preference to any of these, the best option appears to be a vacuum system, which provides uniform hold-down over the test print surface. The only drawback of this approach is its limited flexibility for holding down samples of different sizes.

Locating pins on the x-y stage help in positioning the test sample. These pins guide the top and side edges of each sample to the same position on the stage.

Additional Hardware

Several other hardware elements should be mentioned. The right choice of computer for a given task can be argued in different ways. Clearly, however, Intel-based PCs running Microsoft® Windows are universally available and offer ample software options at reasonable cost.

Also important are stage-mounted calibration targets, permanently attached to the motion stage, that provide for automatic calibration of lighting conditions, resolution, optical density, etc.

To extend the system for additional types of print quality measurements, it can be equipped with spectro-photometers and gloss meters. Backlighting can be added for transparencies.

Finally, an appropriate structure is needed to bind all of the equipment together. It is important that there be no

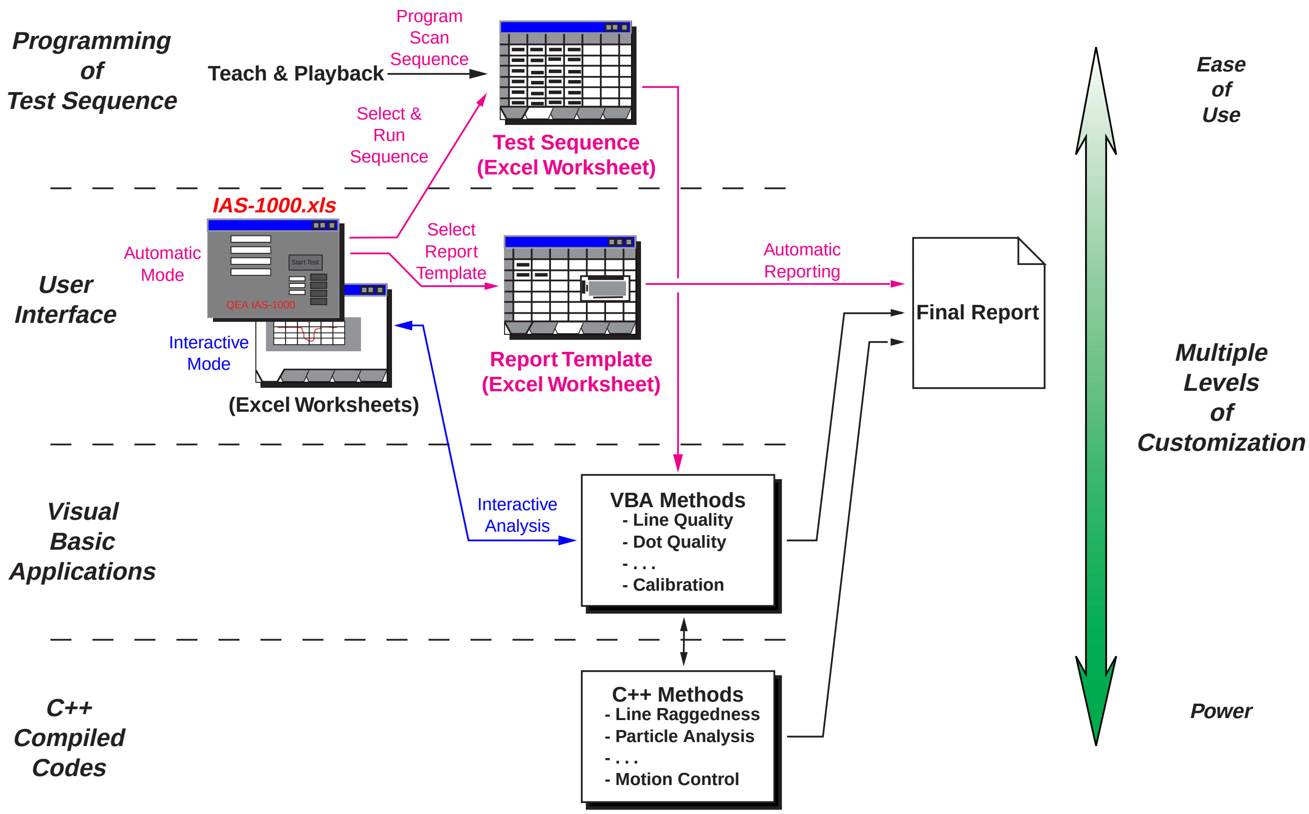

Figure 2 Print Quality Analysis System Software Architecture

relative motion between the camera and the print sample while the image is being acquired. To achieve this, the mechanical structure must be quite stiff and the motion stage must not produce too much vibration. To eliminate external vibration, it is sometimes necessary to use a vibration isolation table.

Software Architecture

A block diagram illustrating the software architecture of our implementation is shown in Figure 2 above. A unique feature of this particular implementation is the use of Microsoft Excel® as the platform for the control software. This design choice provides several major advantages:

- *Compatibility with a popular operating system*. Our system runs in the PC environment under Windows® 95 or later versions. This ensures user familiarity with the operating system and the broad range of application software available for the operating environment.
- *Familiar look-and-feel*. Most users of personal computers are comfortable with Excel and familiar with many basic operations such as formatting, file saving, etc. This greatly reduces the time it takes to become expert users. Furthermore, Excel is equipped with extensive on-line help, and many books and other resources are available to provide support.
- *Powerful reporting features*. The data display, formatting, and charting capabilities of Excel are outstanding for ease of use and flexibility. The user can design report templates so that reports display just the appropriate information in just the right format.
- *Virtually unlimited extensibility*. The open architecture gives the user immediate access to the software for developing new algorithms or improving on existing procedures. High-level data analysis can be done right in Excel worksheets by adding charts, equations, statistical functions, etc. More powerful data analysis can be achieved by programming in Visual Basic for Applications (VBA), which is seamlessly integrated into Microsoft Excel (and in fact is Excel's macro language). For still more complex and time-critical analyses, a high-level language such as C++ can be used to develop highly efficient code that can be linked with the application software by means of DDL or OLE techniques.

Operating Modes

The software is designed for two modes of operation: automated and interactive. In automated mode, the user simply selects a test sequence from a drop-down list and clicks the "Start" button. The system then executes a programmed sequence of moves, measurements, and analyses, and generates a report from an Excel template. The report can be automatically displayed on the computer screen, printed, or saved. The test sequences themselves are programmed in Microsoft Excel worksheets, either manually, or using an efficient "teach-and-playback" method built into the software. In interactive mode, the user can jog the x-y table to any position, perform any available analysis (e.g. optical density, line width, edge sharpness, etc.), and immediately see the results. This mode provides access to much more data than is typically reported in automated mode, allowing the user to efficiently examine new samples, investigate new problems, or prototype new test sequences.

VBA for Automation and System Control

Automation and system control are implemented in Visual Basic for Applications. VBA has three distinct advantages: it is very easy to learn and use, it has extensive capabilities, and it is seamlessly integrated into Microsoft Excel, the platform for the user interface. The user can write simple VBA routines to perform mid-level analyses (for example, computations that require looping, which is impossible to do successfully in the Excel worksheets). All automation routines are written in VBA, so that the user can customize routines or add new routines.

Low-Level Controls, Time-critical Functions and Device Drivers

Dynamic-Linked-Libraries (DLLs) and other object code is used for high-performance and computation-intensive operations. Most of this code is written in the C++ programming language using object-oriented programming techniques. At the bottom of the software hierarchy are the device drivers. These are programs that communicate directly with the hardware devices, such as the frame-grabber and motor controllers.

Image Acquisition, Display and Processing Functions

These are the basic elements found in most commercially available image analysis systems (see Table 1). The basic image processing and analysis tools are implemented at this level. Basic functions include image capture, image display, histogram computation, profile computation, and contour extraction. These functions are necessary for any automated image analysis system, but for systems dedicated to print quality analysis specifically, additional functions are also needed.

Print Quality Analysis Functions

These functions are central to any automated PQ-specific analysis system. They are built upon the basic image analysis functions described above. They can be categorized as follows:

1. Fundamental tools for analyzing dot, line and solid area attributes as outlined in Table 2.
2. Higher level functions such as: bleed and coalescence in inkjet printing; ink drop placement and drop size accuracy for inkjet print head QC; text and character legibility; projection efficiency of transparencies; barcode readability; color gamut for CIELab measurements; and print quality of digitally-printed textiles.

The high level functions are application-specific, and their design usually requires a deep level of understanding of the needs and application requirements of the specific domain of interest.

Table 1 Basic Elements in an Image Analysis System

Image Input Options	▪ Frame grabber(s) ▪ Scanner (e.g. using TWAIN) ▪ Files (e.g. TIFF)
Image Display Functions	▪ Image display (e.g. using VGA driver) ▪ Live video display using frame grabber ▪ Zooming ▪ Non-destructive overlay
Image Manipulation Functions	▪ Filtering ▪ Edge enhancement ▪ Edge detection (extraction) ▪ Binarization ▪ Arithmetic operations ▪ LUT mapping ▪ Morphology ▪ Convolution
Image Measurement Functions	▪ Histogram (any ROI-arbitrary size) ▪ Profile (any ROI- arbitrary endpoints and thickness)
Blob Analysis Functions	▪ Count ▪ Label ▪ Measure ▪ Features Computation (area, perimeter, shape, location, density, etc.)
Output Functions	▪ Print image ▪ Copy image to clipboard ▪ Save image in standard (e.g. TIFF) format

Table 2 The Basic Print Quality Elements

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**

Application Example

A study demonstrating the value of automated PQ analysis was reported recently[10]. The paper described an extensive study of the impact of media on inkjet print quality. The system described here was used in the study to analyze a total of 32 commercially available media types printed on 3 desktop color inkjet printers from 3 different manufacturers. The PQ attributes evaluated included: dot quality (dot size, dot uniformity, and dot gain), line quality (line width, edge raggedness, sharpness, density, and modulation), and solid area attributes (optical density and tone reproduction, image noise in terms of graininess and mottle, and color gamut). Two different evaluation methods were used. Objective analyses were conducted in which carefully-designed test targets were scanned with the automated PQ system. Subjective evaluations were also performed in which a panel of judges rated photographs and pages of text printed on the same media and with the same printers. The study explored the empirical correlation between objective PQ parameters and subjective preferences. To allow for a systematic analysis of the test results, the 32 media types were divided into four groups: uncoated paper, paper coated with a matte finish, paper coated with a glossy finish, and film. From a mechanistic point of view, the results clearly demonstrated the importance of the media surface in controlling ink-media interactions in inkjet printing. Uncoated paper suffered from relatively uncontrolled dot formation due to wicking of the ink by the fibrous structure of the paper. On uncoated papers, the ink drops were irregular in shape and inconsistent in size, and exhibited substantial dot gain. On the other hand, coated papers tended to prevent the dots from spreading, producing consistent, well-shaped dots – the basis of a great picture! These differences are illustrated qualitatively in Figure 3.

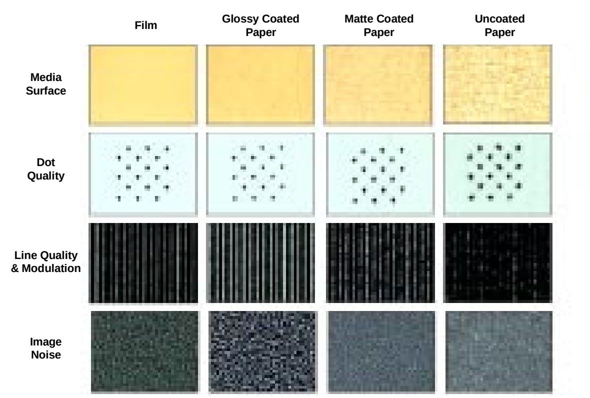

Figure 3 Effect of Media on Print Quality

Figures 4-7 show representative results from the automated PQ analysis system. Figures 4 and 5 show that the roughness of the media (measured in terms of media noise) has a direct impact on dot size (Figure 4) and line quality parameters such as edge roughness (Figure 5). Likewise, increases in dot size and edge roughness degrade the modulation (resolution) and color gamut of the media as illustrated in Figures 6 and 7, respectively.

While these results illustrate the kind of insight that can be gleaned from a well-designed automated PQ analysis system, an equally significant observation is the efficiency of the system in obtaining large volumes of relevant data. In this study, nearly 100,000 data points were obtained and analyzed systematically in a matter of days. With conventional instruments and test methods, it would have taken weeks if not months to accomplish this. The productivity gains attainable with the automated PQ analysis system are striking!

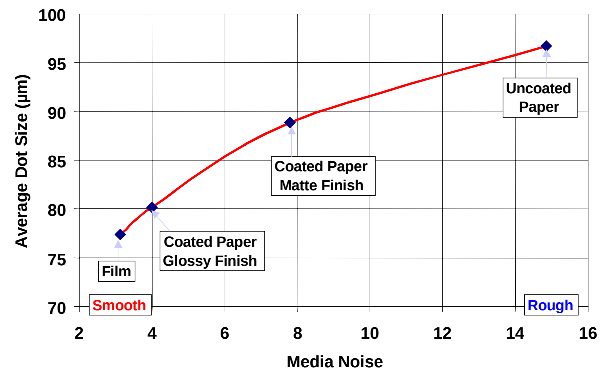

Figure 4 Effect of Media on Dot Size

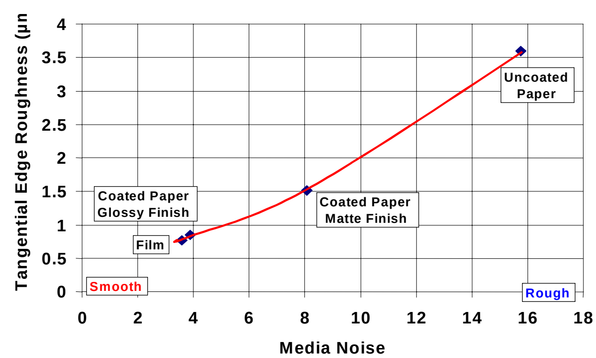

Figure 5 Effect of Media on Edge Roughness

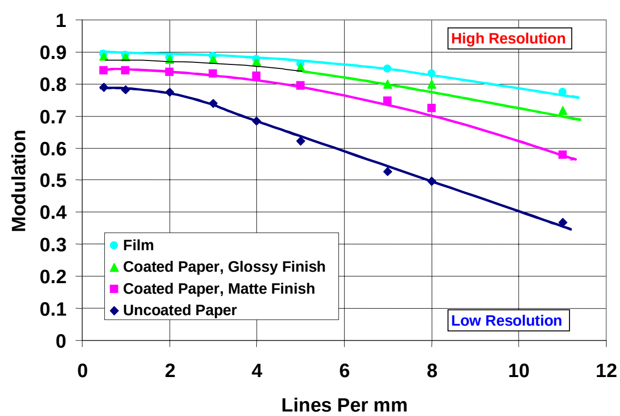

Figure 6 Effect of Media on Modulation

Other studies have similarly demonstrated the effectiveness of the system for electrophotography and thermal printing technologies[11-13].

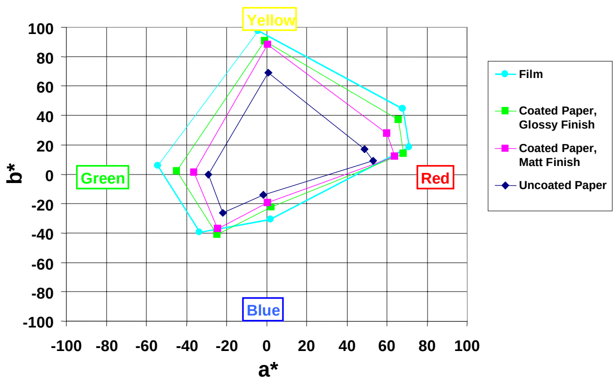

Figure 7 Effect of Media on Color Gamut

Summary

The design of the high-performance automated print quality analysis system described in this paper is based on recognized business needs and user requirements. This paper introduces the reader to details of the design and system architecture. Details of this kind are typically closely-guarded, proprietary secrets seldom described in the open literature, but the authors have chosen to present these ideas in the belief that openness and consensus are the keys to establishing sorely-needed print quality standards for the digital printing industry. To arrive at a consensus on print quality standards and the procedures for quantifying them, the availability of well-understood measurement tools is an essential starting point.

The system described in this paper is novel in its software architecture. Its software and hardware design has been refined over several years of use and testing both in the laboratory and in the field and is now well proven. In the digital printing business, customer satisfaction, time-to-market, and competitive positioning depend on real improvements in productivity at every level — planning, development and production. The difference can only be achieved with intelligent tools that provide the information you need for critical decisions.

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