Image Quality Verification in the Development of Hardware and Media for the KODAK Digital Lab System

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Abstract

Digital photofinishing using silver halide paper offers the high image quality and robustness of traditional optical photofinishing systems enhanced by new options for image flexibility by adding text and graphics, for workflow streamlining, and for print quality improvement through electronic image processing and control.

Part of the price for these opportunities, however, is the necessity to understand and prevent a variety of new image artifacts. In this paper we first describe test methods for measuring the standard image quality parameters and for characterizing digital artifacts, and then outline a systems approach for co-optimizing pictorial and text quality through printer and paper design.

Introduction

The KODAK Digital Lab System, a digital minilab shown at Photokina in September, 1998, is the latest application of technology that has been under development at Eastman Kodak Company for many years and has been used in several earlier professional and commercial systems. Our first papers on digital photofinishing, outlining the design of laser printers and media, were given at the IS&T conference in San Francisco in 1987, and the resulting joint publication[1] is still a good reference for overall design. In this paper we will discuss the design philosophy of the new system with its new requirements for text and graphics. We focus on the laser printer and silver halide paper, identifying key system challenges and the approaches we have taken to solve them. This is, then, primarily a paper about digital system output artifacts, the targets and images used to reveal and characterize them, and the system tradeoffs made, rather than a review of the full set of system specifications and test procedures.

The DLS System

Before setting specifications and developing test methods for a new system, it is necessary to ask two basic questions:

(1). What is the application, and what, therefore, are the key performance criteria?
(2). What technologies are to be used, and, therefore, what characteristic problems must be addressed?

The KODAK Digital Lab System is a stand-alone, self-contained digital photofinishing system for consumer photography. A block diagram of its elements is shown in Fig. 1.

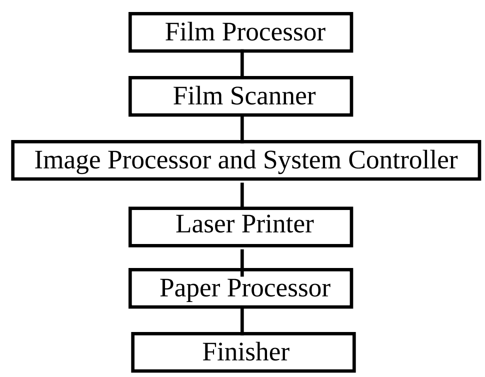

Figure 1. DLS elements

The film scanner, which is described in the accompanying paper by Shafer, uses an area CCD with multiple-wavelength LED illumination to scan APS, 135, or 120 film negatives or transparencies. The laser printer, which is described in the accompanying paper by Narayan, uses three lasers (red, green, and blue) and polygon deflection to raster-scan and expose web-fed, cut-sheet-processed paper from 3.5 inches to 12 inches wide. The special color paper developed for laser printing has been described by Bacilek at previous IS&T Annual Conferences.[2]

The system imaging requirements are that pictorial images be at least as acceptable as those produced by a conventional optical minilab, with improvements in sharpness, tone reproduction, and color reproduction provided by image processing. Setup and calibration must be rapid; stability and reproducibility must be excellent.

The new requirement that caused the most difficulty was that merged files consisting of text and graphics in addition to pictorial images be printed, and that the text quality be excellent.

Image Quality Categories

We divide image quality characteristics into two groups. The first we describe as the classical group, common to optical and digital printing: tone reproduction, color reproduction, sharpness, noise, and geometry. The second group includes considerations unique to a hybrid system: sampling and reconstruction artifacts; paper contrast and text quality; system calibration, contrast, and quantization.

The Classical Set

Tone Reproduction

Our goal is to achieve smooth and continuous reproduction of lightness from minimum to maximum in such a way that gradients are reproduced smoothly, without contouring or posterization, and subject lightness is mapped into the range accessible to the print medium without clipping of shadow or highlight detail. We refer to such performance as achieving "D-min to D-max with grace and robustness." Accomplishing it is critically dependent on printer nonlinearity, paper sensitometry, the number of bits used in lookup tables, and calibration procedure.

We set a D-max value of 2.3 visual neutral density as the requirement for this application. The test targets used are multiple-level neutral step tablets and noiseless computer-generated gradients, while typical test images are close-up portraits, smooth objects such as bunches of balloons, and people in front of shaded near-neutral walls.

Color Reproduction

The maximum available color gamut is set by the choice of image dye couplers in the color paper, although this gamut may not be fully achievable if the laser wavelengths, paper spectral sensitivity, or paper sensitometry are poorly chosen. The narrow exposure bands of a laser system help to make the full gamut available, while digital control permits significantly better accuracy in achieving within-gamut colors because interimage effects such as unwanted absorption can be compensated.

The overall color balance of pictorial images is controlled by the scene balance algorithm of the image processor, while color management within the gamut of the image is handled by ICC profiles.

Our specifications for reproducibility of neutral and colors were chosen to match those of high-quality conventional photofinishing: "one printer button" for color (0.025 log H) and of density (0.075 log H).

The targets used for testing and profile generation include an "eight-cubed" array of color patches containing all combinations of eight levels each of red, green, and blue, supplemented by the Macbeth Color Checker and special targets containing out-of-gamut and other stress colors.

Sharpness

Crisp pictorial images require high system MTF, which in turn requires small laser spots, fast electronics, low-scatter paper, and low flare. A useful design procedure has been published by Yip and Muka.[3] We chose a resolution of 512 pixels/inch and optical spot overlap at 40% for the green record, which give an MTF of 50% at 4 cy/mm and a measured acutance of 93.5 for the paper and printer alone, without electronic sharpening.

Reproducing high-quality text is a significant problem for conventional photographic systems, which we will discuss in the next section. Our specification was that 8-point reversed text (white text on a black background) be clean, and 4-point text readable.

The targets used were an array of square-wave MTF patterns covering the 12" web, each pattern containing fast-scan and slow-scan directions, and a similar array of text samples.

Noise

We classify as noise those artifacts that are not related to image content. They may be periodic or random, caused by the capture device or the printer, and include banding, rastering, streaking, mottle, and grain. Their measurement and objectionability, and the possibility of their masking by broadband noise, have been the subject of many studies; an introduction is given in Ref. 1.

All of them are normally measured using a target consisting of large neutral patches at densities near 0.3, 0.8, and 1.2, scanned with a microdensitometer. Our overall specification was that they could be above the threshold of perception in flat fields, but not above the threshold of objectionability; this is adequate for consumer photography. Even this degree of control is difficult to achieve. A raster-scanning printer has advantages over discrete-element exposing devices in avoiding some of these artifacts.

Geometrical Errors

Geometrical distortion occurs if the fast-scan velocity (or the slow-scan paper transport velocity) is not constant. It is well known that a distortion of 2% is readily detected in the image of a face. Distortion is also unacceptable if several images are printed side by side, such as three 4R prints across a 12" web, to be cut apart at the finishing station. We test distortion by printing an array of single-pixel lines spaced 1/4" apart across the web, then measuring their spacing with a traveling microscope.

Nonuniformity of exposure across the web can be caused by velocity variation or vignetting; it is unacceptable if it gives a visible density or color shift, and especially so for N-up printing.

Color misregistration is a related problem that is highly visible. A tolerance of 1/3 to 1/2 pixel spacing is typical. Fine patterns of alternately on and off lines or pixels are a sensitive indicator of color position or resolution mismatch.

Problems Specific to Digital Systems

In addition to the universal image quality characteristics we have described, there are three system design considerations that can give rise to new types of artifacts that are particularly objectionable because they are not seen in conventional photographic images: sampling, text and graphics, and calibration.

Sampling Effects

Highly visible distortion can occur if the several stages of image manipulation are not done properly. We list three types.

Aliasing: the incorrect reproduction of high-frequency periodic image patterns as lower-frequency ones, caused by sampling during image capture without adequate low-pass optical prefiltering to ensure that no significant input image information exists above the Nyquist frequency of the sampling process.

Resampling: a similar effect to aliasing during image capture, caused by decimating or interpolating an image using non-integral resolution ratios while converting the image to a different number of printed pixels.

Reconstruction: the appearance of "jaggies" on edges, or beats in variable-frequency periodic images such as log-periodic targets, caused by inadequate printer resolution.

The targets we use to detect these problems are patterns of single-pixel lines, typically starbursts, nests of ellipses, and arrays of parallel lines.

Paper Contrast and Text Quality

Both the optics and the media of conventional color photographic systems are optimized for the reproduction of smooth density and color gradients rather than text. They tend to give fringing or flare near sharp, high-contrast edges, and to fill in narrow white lines on dark backgrounds. If the color paper has mismatched D-log H sensitometric curves at high densities, or if the optical spot sizes of a 3-color laser printer are mismatched, this fringing of text and high contrast edges will be colored rather than neutral, which is even more objectionable.

This is not to say that text cannot be well reproduced, but only that the system tradeoffs must be understood. We can illustrate the situation pictorially in a simple way by considering a three-dimensional space in which the *x*, *y*, and *z* axes represent resolution, contrast, and density, respectively, each increasing outward from the center, as shown in Fig. 2.

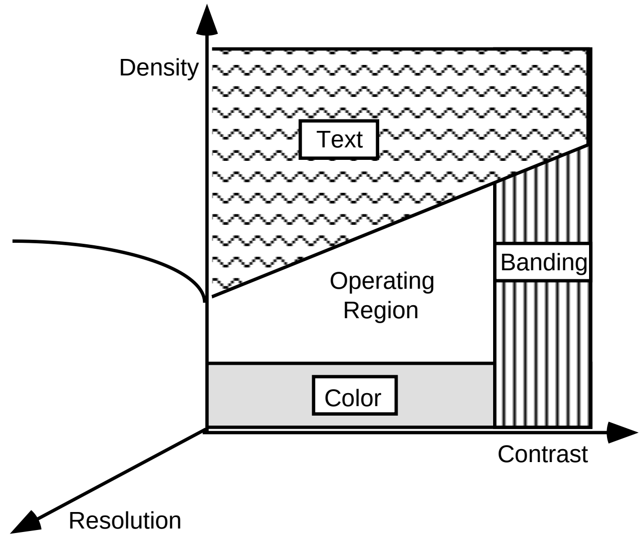

Figure 2. System design space

We determine the permissible operating region as follows:

1. The maximum density achievable must be higher than some minimum value, which will be different for different applications, for acceptable tone reproduction and color saturation. This defines the position of the "floor" of the acceptable region, a plane perpendicular to the z-axis. In Fig. 2, the region of unacceptably low density and therefore color is labeled "Color."
2. If the imaging medium contrast is too high, the unavoidable exposure variations of the printer will give visible banding or other artifacts. For any given printer, this puts a "wall" perpendicular to the y-axis. In Fig. 2, this region is labeled "Banding."
3. The larger the density step at the edge of a text character or graphic element, the higher the paper contrast must be if the transition zone is to be invisible. Hence there is a third surface, a "roof," passing through the z-axis but tilted upward. For any given contrast, this surface sets an upper limit to the density at which text can be written (or, more sensitively, to the density of the background on which white text is to be printed).

   Increasing the resolution of the printer makes the printed transition zone narrower, of course, and hence this third surface is not a plane parallel to the x-axis but rises in the x-direction as indicated in Fig. 2, asymptotically becoming parallel to the x-axis. Higher resolution thus enables higher text density for a given paper contrast.

The region of possible system operation, if there is one, is that enclosed by the floor, wall, and roof of this diagram. This approach is a powerful tool for predicting system performance and identifying which subsystems are the limiting ones. We emphasize that constructing the diagram requires a full knowledge of printer and paper performance.

We have found that a useful test target is a step tablet containing white lines of 1, 2, 4, and 8 pixels width running through the steps. It gives a quick visual indication of the background density at which text fringing will be objectionable for any given printer and paper.

Printer, Paper, and Process Calibration; Quantization

Rapid, accurate, stable calibration is a key requirement of any printing system. For ICC profile color management to work, the printing system must be brought to and maintained in the same standard state in which it was operating when the profile was created.

A common choice in the photographic industry has been to set up the printer so that equal image code values CV produce equal Status A red, green, and blue densities, which print a patch that is approximately neutral, and scaled so that the densities are equal to CV/100. Hence the CV set (100,100,100) gives Status A densities (1.00,1.00,1.00), and the 8-bit CV range 0 to 255 gives density 0 to 2.55 (or at least it is linear between D-min and D-max).

Although measurements will continue to be made using ubiquitous Status A densitometers, it is not necessary that equal CV give equal Status A values, nor that the densities be linearly proportional to the CV. For example, some groups set up their printers so that CV is proportional to CIE lightness L*, and equal CV give a*=b*, a colorimetric neutral. Such a configuration can be described by three separate nonlinear curves of R,G,B Status A densities versus CV.

The reason why nonlinear calibration may be desirable is to help avoid quantization artifacts, seen as contouring of images. In general, eight bits of image information, corresponding to equal density increments of 0.01 density, give enough density resolution to avoid contouring in all practical cases except possibly for noiseless computer-generated ramps. Achieving this calibration requires that neither the printer nor the paper be too nonlinear, and that all lookup tables have at least ten bits and preferably twelve. Calibrating in equal L* steps gives smaller density increments at low density, where artifacts are more easily seen, and larger increments at high density, where artifacts are less visible.

Summary

Tone and color reproduction, sharpness, graininess, and geometrical distortion can be tested using similar methods in optical, digital, and hybrid systems, although the added flexibility of the latter two require more elaborate testing to check their full capability. New types of artifacts occurring only in scan printing, such as banding and sampling, require new tests. The merging of pictorial images with high quality text and graphics, a new capability brought to photography by such systems as the KODAK Digital Lab System, requires a thorough systems understanding of hardware and media interactions.

Acknowledgments

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References

1. R. R. Firth, D. Kessler, E. Muka, M. Naor, and J. C. Owens, *J. Imag. Technol.*, **14**, 78 (1988).
2. John F. Bacilek, The Efforts of Eastman Kodak Company to Produce a Direct Digital Output Silver Halide Color Paper, *Proc. IS&T 50th Annual Conf.*, 242 (1997), John F. Bacilek and Charles H. Whitfield, Direct Digital Output Silver Halide Color Media and the Market Response to this New Capability, *Proc. IS&T 1st PICS Conf.*, 15 (1998).
3. K. Yip and E. Muka, *J. Imag. Technol.*, **15**, 202 (1989).