W1.1 Image Quality of Printers **W1.1 2002 – 020**
Effective Resolution
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April 10, 2002

An Objective Resolution Metric for Digital Printers

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Abstract

Resolution is a measure of the ability of an imaging system to reproduce fine details, something an increasing number of digital printer users care passionately about. Despite this interest, resolution is not routinely measured or specified by printer manufacturers. Among the reasons is the absence of industry standard resolution metrics for digital printers. In this initial paper, the authors explore some of the reasons resolution metrics for digital printing systems are not well established or widely used. In particular, we examine the idea that printer resolution can be determined from input test patterns composed of arbitrary or continuously varying spatial frequencies. Methods based on this approach risk confounding information losses due to image sampling with printing limitations of the system under test. We propose an alternative metric based on test patterns that are matched to the addressability of the target printer. A procedure for measuring prints of these test patterns and determining resolution from those measurements is described. It is hoped that printer manufacturers and others with an interest in printer resolution will evaluate this proposed metric and contribute to its refinement and adoption as a standard for defining, measuring and reporting this important imaging characteristic of digital printing systems

Introduction

Objective resolution metrics for digital cameras and image scanners are well-established as industry standards[1,2], yet corresponding resolution metrics for digital printers are not widely used and have not been standardized. This disparity is partly explained by historical differences - digital cameras and scanners inherit a rich legacy of resolution metrology from film-based photography, while the resolution of digital printers is often evaluated by subjective methods adapted from offset printing. A second reason is that the resolution of digital cameras and scanners is routinely measured and reported, while the resolution of digital printers is not frequently specified or measured. The paucity of resolution information has led many printer users to mistakenly conclude that resolution is not important in digital printing systems, or worse, that "addressability", the ubiquitous "DPI number", is synonymous with "resolution". This is untrue because many printing systems cannot resolve image detail at the scale of their own pixels and, where such detail is resolved, it may not be visible to the eye.

Definitions

Terms important to resolution metrology are defined here for digital printing systems. These definitions are consistent with generally accepted usage in related fields.

Dot has a context-dependent meaning. It usually means "pixel" (as in dots-per-inch), but sometimes it refers to a halftone dot - which is unrelated. Occasionally it takes other meanings as well. Due to its inherent ambiguity, this term should be used with care, if at all.

Pixel, or picture element, is the smallest area of an image for which the full tone scale is specified. An image with 24 bit color, for example, associates three 8-bit numerical values with each pixel in the image. Note that continuous tone images are almost always halftoned which typically aggregates colorant more coarsely than the pixel spacing.

Addressability is the number of pixels per inch that are independently specified in an image. Individual pixels are not necessarily printable, nor are they necessarily resolved in printed output or by the viewer's eye if they are printed. Horizontal and vertical addressabilities may differ. Most printer manufacturers specify addressability in dots-per-inch, where "dots" is understood to mean "pixels".

Resolution is the maximum number of alternating black and white lines per inch that can be printed with sufficient contrast to be distinguished by the eye. Resolution can equal but not exceed addressability, although it rarely does so. Resolution measures the ability of a printer to reproduce fine structure in an image. Unlike addressability, resolution is directly related to perceived image quality. We chose to report resolution in lines-per-inch (LPI) rather than line-pairs-per-inch (LPPI) to make reported resolution directly comparable with addressability in "DPI".

Contrast, defined and discussed more completely below, is a calculated measure of the perceived reflectivity difference between unprinted white spaces (Rw) and printed black lines (Rb). According to this definition Rw-Rb is not divided by Rw+Rb, as is common practice elsewhere.

Background

The need to measure resolution has been addressed many times in the imaging sciences and most efforts to measure resolution in digital printers draw from existing methods. Considerable care must be exercised in developing a printer metric based on methods developed for cameras and scanners, however, because most such approaches assume the ability to define input test patterns having a continuum of arbitrarily-defined spatial frequencies[3]. While such test patterns generally work well for cameras, which are normally presented with "input" object scenes having a broad spectrum of spatially frequencies, digital printers ultimately require the input file to be sampled at the printer's pixel spacing. Consequently, a properly sampled input test pattern can contain only certain line widths and cannot even approximate most arbitrary or continuously varying spatial frequency patterns near the resolution limit.

Spatial image sampling is a defining characteristic of digital printer input and output that profoundly affects resolution definitions and metrics. Ironically, as digital printers and their associated drivers have become ever more powerful image processors, it has become easy to overlook the core reality that digital printers still require digital input. Most printers will accept and resample input image files with almost any addressability. This contributes to expectations that a printer should not only print arbitrarily sampled input, it should be evaluated on its success in doing so. A 600 DPI digital printer, for example, cannot print 1.25 pixel wide lines alternating with 1.25 pixel wide spaces. Consequently, it cannot reproduce a 480 LPI (240 LPPI) test pattern, even though the user can easily define such a print job. Should this limitation be regarded as a defect in the printer?

It is essential for a printer resolution metric to come to terms with this question. The authors consider information losses due to image sampling to be inherent in digital imaging, rather than a limitation specific to a printer. While we recognize that many printing systems have the ability to resample images, we do not believe that a resolution metric should assess the effects of resampling on otherwise "unprintable" test images. Instead, we want the metric to assess the resolution capabilities of the printing system given a "properly sampled" input file. Such a file removes resampling issues from the proposed metric by matching the addressability of the test pattern with that of the printer under test, establishing a pixel-for-pixel correspondence between the image file and the printed output. This approach follows widely accepted practice for formatting printer input where "best quality" prints are desired. Properly sampled input fully and unambiguously defines the resolution test pattern at the pixel level, protects it from resampling, and disallows the input of unprintable images.

By making this choice, we have defined the printer's input interface in the digital workflow as the point at which all images are properly sampled. We regard initial image sampling and capture, together with subsequent editing and resampling, to be pre-processing functions regardless of the device which performs them.

Approaches that require or allow resampling of the test pattern are vulnerable in two respects. First, because they fail to adequately determine printer performance at the few, but critical, spatial frequencies near the resolution limit that are printable, and second because they confound information losses due to image sampling limitations with the printing limitations of the system under test.

Limitations of MTF Methods

While resolution metrics based on modulation transfer functions (MTF) have enjoyed great success when applied to systems which create digital images from continuous objects, MTF-based methods have not fared as well for printers. Sampling limitations undermine two fundamentals of MTF methods. First, the basis functions for Fourier series are sine and cosine waveforms, which can neither be input to nor output from digital printers at spatial frequencies important to resolution measurement. Rectangle-wave patterns, which are printable at selected frequencies, have infinitely broad spectra and cannot serve as Fourier basis functions. Second, most MTF methods rely on varying the input spatial frequency over a continuous range of values especially those near the limiting resolution of the system, yet digital printers can output only a few discreet spatial frequencies near the resolution limit. A third and potentially deeper concern is that printers are not linear systems, which compromises the meaning and value of MTF-based methods for evaluating their performance[4].

Purpose

Our intent is to develop a resolution metric for digital printing systems that enables meaningful determination of resolution from the measurement of print samples. We would like the metric to have the following attributes:

1. Readily understood and implemented.
2. Consistent with similar metrics used in related fields.
3. Satisfies digital printer addressability requirements.
4. Produces repeatable and reproducible results.
5. Does not rely on human observers.
6. Is applicable to most digital printing technologies.
7. Gives results that agree well with visual perception.
8. Gives results that are meaningful to printer users.

Overview of the Method

Reconciling these attributes with the capabilities of digital printing systems led to the following observations and decisions. Collectively, these create the framework for the proposed metric:

1. While resolution is determined from a print sample produced by a printer, it is regarded as a property of a "printing system" which includes the printer,

consumable colorants, print media and printer software, all of which affect measured resolution.

2. Resolution in printed output is not considered meaningful beyond the resolution limit of the human visual system. Unlike photographic film, which is subject to later enlargement, digital prints are regarded as an end product intended to be viewed by the unaided eye. The method is not applicable to transparencies, machine-read labels, etc.
3. Printed patterns are evaluated in the space domain rather than the spatial frequency domain. This produces results that we believe are more readily understood in terms of visual experience. It also enables us to develop a visual contrast threshold function (VCT) that describes human visual response to printed test patterns, making the results more meaningful to most printer users.
4. Resolution is measured and reported for black only. This choice recognizes that perceived image sharpness is dominated by the visual luminance channel. It also enables resolution measurement for both color and monochrome (black only) printers, while avoiding difficulties raised by other colors. Process black is used where device black is not available.
5. Resolution is determined from measured image contrast plotted as a function of lines-per-inch, and is determined in a two-dimensional space having contrast as the ordinate dimension and lines-per-inch as the abscissa dimension.
6. The terms “lines-per-inch”, “LPI” and “line frequency” are used interchangeably to describe test patterns with rectangle-wave profiles. Lines-per-inch is a space-domain quantity and not to be confused with “spatial frequency”, a frequency domain quantity. A line pattern having a rectangle-wave profile and a single “LPI value” contains an infinite number of spatial frequency components.
7. The primary “resolution number” which is always reported by the metric, is the number of resolvable lines-per-inch.
8. A secondary “resolution number”, which may not always be reported, is the contrast value at the limiting resolution. This value carries additional information that will interest some users.
9. Where a printer’s resolution differs in the two principal directions, resolution is determined and reported for both the “process direction” (Y), parallel to the paper’s motion through the printer, and the orthogonal “scan direction” (X).
10. The test pattern image file defines a binary tone level image with all pixels at 0% or 100% print density. This density setting effectively prevents printers from halftoning the test image, which would modify it at the pixel scale and render printed output unusable for determining resolution.
11. Printed test patterns consist of parallel black lines with unprinted intervening white spaces, similar to many classic “bar charts”. A series of test patches is printed within each test pattern. Line and space widths within each patch are defined to be an integral number of printer pixels. Where possible, lines and spaces are of equal width, defining a 50% duty cycle square-wave reflectivity profile.
12. We define contrast as Rw-Rb, where Rw and Rb are spatially averaged reflectivities of white spaces and black lines. Measured reflectivities range from 0 to 1, limiting contrast to values between 0 and 1 without further normalization. We avoid division by Rw+Rb to make contrast more representative of human perception. Dividing by Rw+Rb raises the contrast of dark line pairs and lowers it for light line pairs having the same reflectivity difference, exactly the opposite of visual response. Our definition also desensitizes the contrast to variations in Rw+Rb, which is important for digital printers where poorly resolved test patterns often devolve onto black or a very dark gray, rather than a mid-level gray. Spatial averaging in the calculation of Rw and Rb emulates the effect of spatial noise on perceived contrast.
13. In determining resolution, contrast values are linearly interpolated between measurable test patch line frequencies but are not extrapolated beyond the last measurable line frequency.
14. An experimentally determined visual contrast threshold (VCT) function establishes the contrast level required by the human visual system to reliably detect the presence of line patterns on reflective media as a function of line frequency. Test pattern line frequencies having a measured contrast greater than the corresponding VCT value are defined as “resolved” while those with lower contrast are “unresolved”.
15. Three similar test patterns are printed at the center and diagonally opposite corners of the test page. All three patterns are measured, reducing the influence of banding and other spatial variations in printed output that potentially affect measured resolution.
16. Media properties, particularly reflectivity or “brightness” affect measured contrast, and therefore resolution. While these effects could be treated as unwanted perturbations, we view the printer and print media as part of a printing system and use the manufacturer’s recommended media for “Best Quality” or “Photo” printing mode as described in the printer’s operating instructions.
17. The reflectivity of solid-area black colorant differs among printers. These variations affect measured contrast and calculated resolution. Solid area black reflectivity is also a visually significant property of the printing system which affects perceived contrast and resolution. Consequently, no attempt is made to “correct” it.
18. Reflectivities are measured in diffuse illumination. The illuminator geometry ensures that specular reflections from the print sample do not reach the CCD, desensitizing the measurement to media and colorant gloss.

Printing Test Patterns

The Image File

Multiple versions of a standard image file have been created. Each version has an addressability that matches the addressability of a subject printer. The test pattern, a portion of which is shown in Figure 1, contains twenty-six test patches. Twenty-four of these patches consist of alternating lines and spaces having constant width; twelve have horizontal lines and twelve vertical. Reference areas for solid black and media white make up the remaining two patches. Patches are numbered according to line width measured in pixels to facilitate identification.

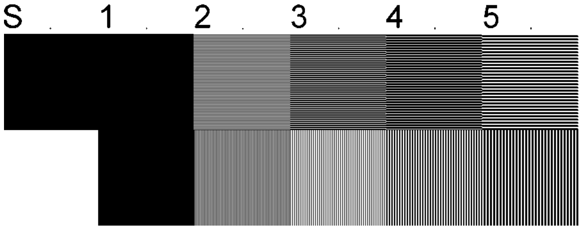

Figure 1. A Portion of the Test Pattern at 1:1

Six patches define horizontal lines and spaces of equal width at 1, 2, 3, 4, 5 and 6 pixels per line. Six additional patches define horizontal lines and spaces of unequal width at 1/2, 2/1, 2/3, 3/2, 3/4 and 4/3 pixels per line/space, allowing printer resolution to be measured for 7, 5 and 3 pixels-per-line-pair. Each of these twelve patches is duplicated in horizontal and vertical orientations. The test pattern for a 600 DPI printer includes the following line frequencies: 600, 400*, 300, 240*, 200, 171.4*, 150, 120 and 100 LPI. LPI values with an asterisk cannot be reproduced at 50% duty cycle. All printable line frequencies above 134 LPI are included in this series. Three “copies” of the test pattern are reproduced on the test page at the upper left, center and lower right

Printing the Test Page

Density controls are used in their “normal” or default settings, except where users are instructed to select other settings for “Best Quality” or “Photo” printing. The test pattern must not be half-toned, rotated, compressed or otherwise altered at the pixel level. The resolution test page is printed on media recommended by the printer manufacturer for “Best Quality” or “Photo” printing mode. When more than one media type is recommended, results for the print media giving the highest resolution are reported. Prints are made using fresh consumables and following the manufacturer’s recommended procedures for “Best Quality” or “Photo” printing.

Figure 2 shows a photomicrograph of a 600 DPI print sample having two-pixel-wide lines alternating with two-pixel-wide spaces. The numerous small irregularities visible here are typical of the spatial noise present in many digital prints.

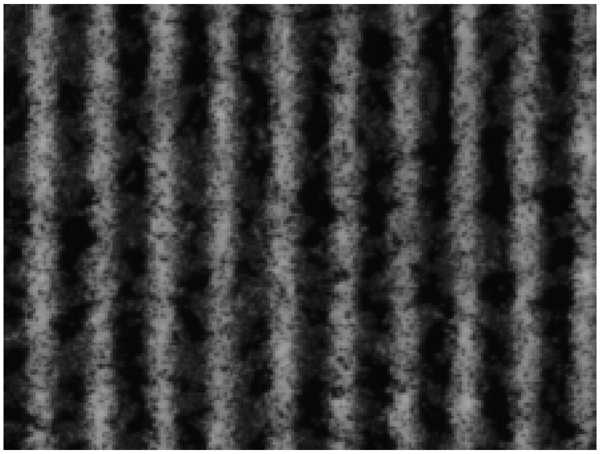

Figure 2. Photomicrograph of Printed Test Pattern

Measurement and Data Reduction

At a microscopic scale, monochrome digital prints approximate binary tone level images regardless of their perceived tone scale when viewed at normal distances. Tone scales are typically produced by halftone methods that rely on spatial integration by the eye to cause perceived tone variation. Similarly, the reflectivity of lines and spaces in a resolution test pattern does not vary as a function of line frequency at the microscopic scale. Instead, the shape and position of line edges become irregular, areas of unwanted colorant appear in white spaces and irregular unprinted areas appear in black lines. Collectively, these numerous small irregularities constitute spatial noise in the image, with the spatial “signal-to-noise-ratio” typically decreasing as line frequency increases. While much of this spatial noise is unresolvable by the eye, it reduces perceived contrast when integrated by the visual system. The resolution metric uses spatial signal averaging to emulate this reduction in perceived contrast.

Printed test patches are imaged onto the CCD array of a radiometrically calibrated CCD microscope. Spectrally broad illumination is provided by a fluorescent ring-light arranged to reject specular reflections. The print sample is rotationally aligned so that printed lines in the test patch, when imaged onto the CCD array, are parallel to CCD pixel columns. The image is captured and the reflectivity associated with each CCD pixel is calculated and written to a data file. Each CCD pixel row captures an individual reflectivity profile across multiple lines of the test pattern. The mean reflectivity value for each column is calculated, and the suite of mean values forms a composite reflectivity profile for the test patch.

This averaging process reduces image noise in the composite profile, and establishes the peak (white) and valley (black) reflectivity levels for each cycle of the composite profile. These peak and valley reflectivities are a sensitive measure of image noise and this averaging procedure is central to establishing measured image contrast. To ensure adequate spatial sampling of the test print during reflectivity measurements, the authors used a CCD microscope that images each 600DPI printer pixel across 16 CCD pixels.

Figure 3 illustrates an individual reflectivity profile (dashed line) and the corresponding composite reflectivity profile (solid line) for the test patch shown in Figure 2.

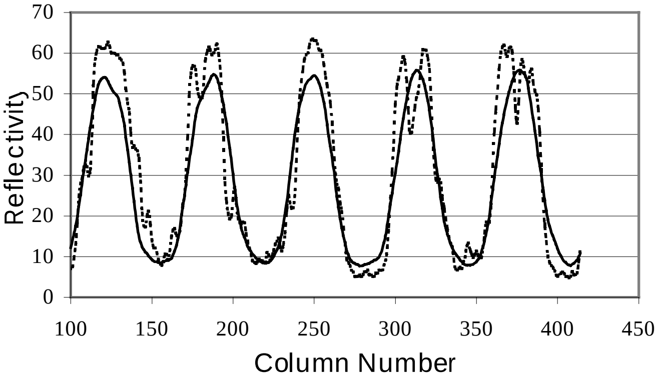

Figure 3.Individual and Composite Reflectivity Profiles

The composite reflectivity signal is then peak detected and the mean values of the peaks Rw and valleys Rb are calculated. The peaks and valleys are also counted. If their number differs from the expected number by more than an incidental error, the measurement fails. This step helps protect the result from banding or aliasing artifacts. An additional averaging step is needed for test patches having an odd number of pixels-per-line-pair (PPLP). For example, two test patches were printed with horizontal lines at 7 PPLP, one with 3/4 and one with 4/3 pixels per line/space. The mean value of Rw is found for these patches, and the mean of the two Rb values is likewise determined. While neither of the patches is at 50% duty cycle, their mean values is used to represent that unprintable case.

The contrast Rw-Rb is calculated for each test patch, and the contrast values are plotted against their respective LPI values. Adjacent data points are connected with straight-line segments. Contrast values which fall below a yet to be determined noise threshold are considered invalid and are not used. Two plots result, one for horizontal and one for vertical lines. It is important that neither plot be extended beyond the LPI value of its last valid data point. Contrast data in X and Y directions for two printers are plotted in Figure 4. The superior resolution of Printer 2 is evident in the figure. Note that only line frequencies having an even number of pixels-per-line-pair are plotted.

Determining and Reporting Resolution

As indicated by the dashed line in Figure 4, the visual contrast threshold curve (now under development) is superimposed on plotted contrast measurements and the coordinates of their intersection points are found, where present. If either contrast plot fails to reach the VCT curve, the coordinates of the last valid data point are found, instead. It is expected that the contrast plots for some printers will not reach the VCT curve. The reported resolution values are the coordinates just described, with the LPI value being primary and the contrast value secondary. Results are reported for both X and Y directions.

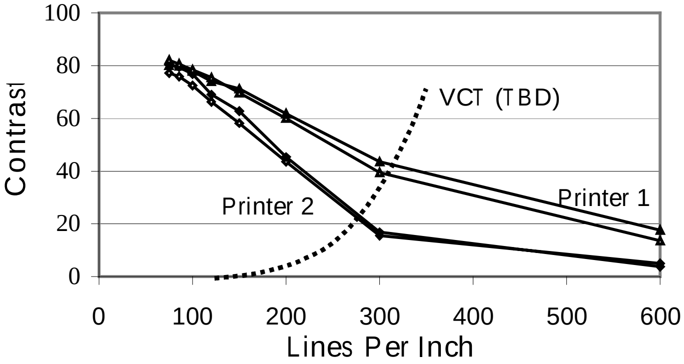

Figure 4.Measured Contrast for Two Printers

Interpreting Results

The interpolated approach taken here has a number of similarities to VESA 303-7[5], a resolution standard for flat panel displays. Linear interpolation is used in both methods to span unreproducible frequencies in pixellated output. This interpolation should be regarded as a construct that allows a discontinuous quantity (resolution) to be determined over a continuous range of values without intending to suggest that reported values are necessarily realizable. If this seems discomforting, we feel it is superior to methods which suggest the ability to input print test patterns that cannot survive reconciliation with the printer's sampling requirements.

Visual Contrast Threshold Function

The VCT function establishes the contrast level required by the eye to reliably detect the presence of square-wave line patterns in printed output. The contrast sensitivity function of the human visual system was first determined by Van Nes and Bouman[6] for luminous displays, and later extended to reflection prints by Burningham and Bouk[7]. While these studies have established the basic methodology for defining a visual contrast threshold function, their results are not directly applicable to our purpose. Sinusoidal patterns were used in both cases, for example, whereas the resolution metric described here makes use of square-wave target profiles and a modified definition of contrast. Our intended use departs sufficiently from the conditions under which existing contrast sensitivity functions were determined to warrant its experimental regeneration. The development of a visual contrast threshold function consistent with the proposed resolution metric has been initiated and will be reported upon completion.

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