Banding Characterization for Inkjet Printing

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Abstract

A significant challenge for developers of inkjet printing technologies is achieving uniformity in areas of solid color. Non-uniformities can generally be classed as either two-dimensional, including such phenomena as graininess, coalescence and mottle, or one-dimensional, usually termed banding. Banding is often the most objectionable print quality problem in digital prints. Much research has been done into human perception of banding, but developers of digital printing systems have typically not had access to test equipment that would allow them to capitalize on this work. In the absence of appropriately designed test methodologies, they have lacked the means to quantify banding in their products, either by tracking progress in product development or monitoring banding in production. Enough is now understood about banding measurement for practical steps to be taken to address this widely-recognized problem. This paper will discuss banding measurement from a practical engineering perspective, based on a technique implemented in a commercially available print quality analysis system. The discussion will focus on how this technique can be applied to inkjet printer development, identifying key factors affecting banding and describing "metrics" for quantifying its magnitude. Progress in developing an international standard for banding measurement, and its importance in the context of existing standards, will be discussed.

Background

Manufacturers of printing equipment work diligently to deliver defect-free images. Despite these efforts, some all-too-common printing defects persist. One of these is banding – the appearance of objectionable variations in areas intended to be uniform in color or optical density. Banding is generally the result of small mechanical, electrical, or even chemical imperfections in the printer components and extends across the page vertically or horizontally. R&D to improve these components can increase costs without necessarily fixing the problem, and components may degrade in the field, producing banding problems that did not exist at the time of shipment. Given the prevalence and importance of the issues involved, printer companies continue to examine the problem closely.

There are two key aspects to the interest in banding. One is the relationship between banding and human perception, affecting such things as acceptance criteria and purchasing decisions. The other is the need for methods product developers can use to diagnose causes of banding in order to correct them. Many researchers have studied human perception of banding,[1,2] usually basing their findings on subjective evaluation of samples containing sinusoidal reflectance variations at fixed frequencies. Results of these studies show that human vision is limited to about 10cycles/mm at typical viewing distance, as shown in Figure 1. The studies attempt to determine the lowest levels of contrast at which banding is perceptible to the human eye. In principle, this approach should be useful in setting acceptance limits for banding. In practice, the fact that printers create banding at multiple frequencies simultaneously complicates the application of this research.

Another body of research focuses primarily on banding problems as they relate to specific printing technologies. Ng[3] has examined the problem of banding in relation to electrophotographic printing. Haas[4] has studied it in relation to digitally exposed photographic media. Each printing technology has its own unique problems that can result in banding. Focusing less on the science of human perception and more on printer engineering, this body of research provides feedback that points to the causes of the problem, e.g., which component in a laser printer is the cause of a given banding problem. Greater understanding of both human perception and optimal hardware design is needed to make progress, and there is much work to be done in both areas.

Another area in which much work remains but which serves as an important impetus for progress is the push to develop widely-applicable, widely-accepted print quality standards. The International Standards Organization's joint technical committee ISO/IEC JTC 1/SC28 will shortly release a new international print quality standard, ISO-13660, intended to systematize measurement of 14 key print quality attributes. Additional metrics will be added to the standard as time goes on. A new work item on the committee's agenda is to develop a method for measuring banding. The goal is a fast, automated measurement technique that is as simple as possible and inexpensive to replicate, and whose results correlate well with human preference. A starting point proposed by the committee is a technique developed by a laser printer manufacturer, in which the area to be scanned is measured with a 300dpi flatbed scanner and a reflectance profile is developed. An FFT is computed and the resulting data are normalized by the human visual spatial sensitivity. The results are then factored into an number that rates overall banding severity. This approach is not without drawbacks, but it offers a good platform to build on. The experiments below, among others performed with the commercially available automated image analysis system described, are expected to advance progress toward an acceptable banding algorithm for the ISO-13660 international print quality standard.

Introduction

The purpose of this study was to quantitatively assess the effects of multi-pass print modes, an approach commonly used in ink jet printer design to minimize the visual impact of banding. In multi-pass print modes, multiple nozzles are used in several passes to print each complete row of dots. In 2-pass mode, for example, the first pass of the carriage prints half the dots required to complete the row. The print media is then advanced half the height of the row, or "swath," and the missing dots are filled in during the second pass of the carriage. If one of the nozzles is mis-directed or is not firing, the multi-pass technique helps to hide the defect since half the dots are fired from a different nozzle. In 3-pass mode, a third of the dots are filled in during each pass, and the media advances by one-third the height of the swath.

To quantify the severity of banding and the efficacy of different numbers of passes in masking it, samples printed on an Encad NovaJet 700 printer were evaluated using an IAS-1000 Automated Image Analysis System (QEA, Inc.). Among the print quality metrics built into the IAS-1000 software is a banding analysis tool, which scans a long area of the sample at high magnification, acquiring reflectance data. The results can be viewed in the spatial domain as reflectance profiles or in the frequency domain. The banding tool provides valuable information about characteristics such as the component frequencies of the banding. This kind of information is useful in diagnosing the mechanical, electrical, or other sources of the problem. The goal of this research is to advance progress toward developing a single metric for characterizing banding severity.

Test target design

In developing diagnostic methodologies for automated print quality analysis, appropriate design of the test target is critical. In this case, the test target consisted of 16 long rectangular blocks of color. The blocks were cyan, magenta, yellow, and black in tints of 30%, 50%, 70%, and 90%*. Each block was 219×11mm (8 5/8'×7/16'). The test pattern was designed to be printed on a 216×279mm (8 ½'×11') sheet. The banding tool uses Fast Fourier Transforms (FFTs), a technique that requires many occurrences of a pattern to determine the frequency accurately. The extended length of the color blocks was needed to allow for accurate determination of banding frequencies.

Sample preparation

The Encad NovaJet 700 printer was selected because, as is common in ink jet printing, it produced noticeable banding in single pass mode. No attempt was made to optimize the print head. The samples were printed using uni-directional printing in 1-pass, 3-pass, 4-pass, 6-pass, 8-pass, and 10-pass modes.

Measurement technique

The IAS-1000 includes a cabinet with X-Y positioning stage, calibrated 2-D CCD camera, high-resolution optics, light source, proprietary control software and frame-grabber. The built-in banding analysis tool develops a reflectance profile of the sample[5] by averaging the reflectance values over a certain width, typically 1 to 4 mm, within the color block and steps the camera through a series of positions until the full length of the block has been scanned. The tool uses FFTs to determine the component frequencies of the reflectance profiles. The software automatically identifies the magnitude and frequencies of the ten most prominent peaks in the frequency plot.

In addition, the software has the capability of producing frequency plots weighted by the human Visual Transfer Function curve (VTF), as shown in Figure 1. An inverse FFT on this frequency data can be used to construct a new reflectance profile filtered by the human VTF. This technique can help to pinpoint banding that is objectionable to human observers. We plan to explore the potential of the VTF function for use in a banding metric, but for this particular study, the VTF function was not used.

* The percentage means the percent of dots printed in the area. Due to dot gain, these areas are darker than they would be if the values indicated percent area coverage.

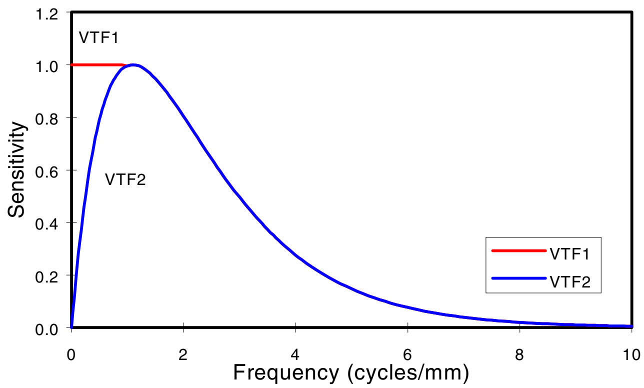


Figure 1: Human visual transfer function (VTF) or spatial sensitivity curve. There is some disagreement in literature about the most appropriate shape of the curve for frequencies less than 1 cycles/mm.

To perform the measurements, an automated test sequence was created which analyzed all 16 color blocks on the test target. The camera magnification was set to 5µm/pixel. The scan was set up to average reflectance values over a 3mm width, with a step size of 0.2mm, and a measurement length of 166mm.[6] To reduce the amount of data, the reflectance profiles were downsampled by a factor of 5X (one data point every 25µm). This effectively filtered out data above 40cycles/mm in the spatial domain. (All points, however, were used in the Fourier analysis).

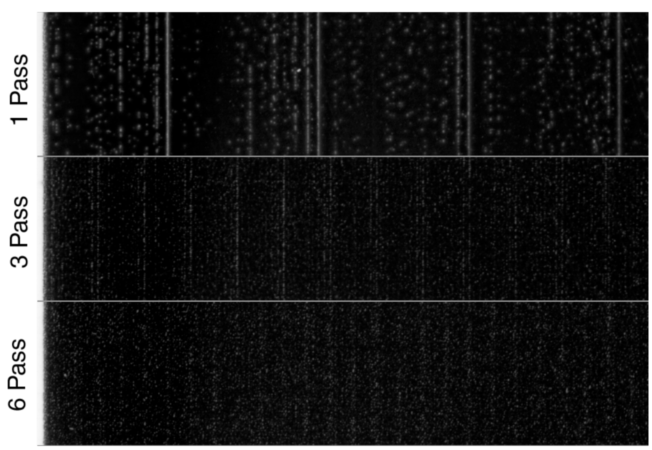


Figure 2: Scanned images from banding samples. Scanned on a HP4C at 600 dpi. Images are shown at 2X magnification.

Analysis

Figure 2 shows some representative images from the samples[†] which show that the multi-pass print modes were effective in reducing subjective banding severity. In the 1-pass mode, defective nozzles produced white bands across the page every 8.824mm (0.347'), the swath height of the Encad NovaJet 700 printer. In 3-pass mode, the white bands were more closely spaced, at 2.717mm (0.107'), but were fainter and less noticeable. At 6 passes, the spacing was still closer and the bands had become still less obvious.

Perceived severity of banding is dependent upon:

1. the contrast between the bands and the surrounding field,
2. the spatial frequency of the banding, and
3. the viewing distance between the observer and the samples.

To a point, multi-pass printing increases the frequency and minimizes the contrast of the bands. However, there appears to be a point of diminishing returns to the observer in using this technique. After about 4 passes, additional passes provide much less reduction in perceived banding.

Our quantitative data are in keeping with the subjective impression of the samples. Figure 3 shows reflectance profiles and frequency information for the 1-pass, 3-pass, and 6-pass samples in the 70% black tint area. The 1-pass samples have a light band (20 to 25% reflectance) every 8.824mm. This translates to a frequency of 0.113 cycles/mm and can be seen as the first peak in the frequency plot. The rest of the frequency plot consists mostly of the harmonics of this fundamental frequency (0.227, 0.340, 0.453, etc.).

Compared to 1-pass mode, the bands produced by 3-pass mode have lower reflectance (i.e, they are darker). In 3-pass mode, all of the peaks are below 5%. However, there are three times as many of them, one every 2.717mm. This translates to a fundamental frequency of 0.368cycles/mm as shown in the frequency plot. Again the harmonics of this fundamental frequency can be seen (0.739, 1.106, 1.466, etc.).

Figure 3 also shows data from a 6-pass sample, whose reflectance profile shows little discernable banding. The FFT, however, pulls out a peak fundamental frequency of 0.74 cycles/mm and its harmonics.

Discussion

How, then, should one interpret and apply the information in the graphs in Figure 3? The answer probably depends on whether the purpose is to determine the acceptability of the banding or to get diagnostic data in order to fix it.

Perhaps the most important diagnostic information is the fundamental frequencies in the banding. In the samples under test, the source of the banding was known a-priori, but in practice, there are multiple potential sources. The fundamental frequencies provide an important clue to the cause.

In trying to evaluate the perceived severity or acceptability of banding, more analysis is needed. Obviously, there is a connection between perceived severity and the reflectance profile and frequency data in Figure 3. But what is the key metric for describing the severity?

[†] It should be noted that Figure 2 is a scanned image and can give only a rough impression of the original samples.

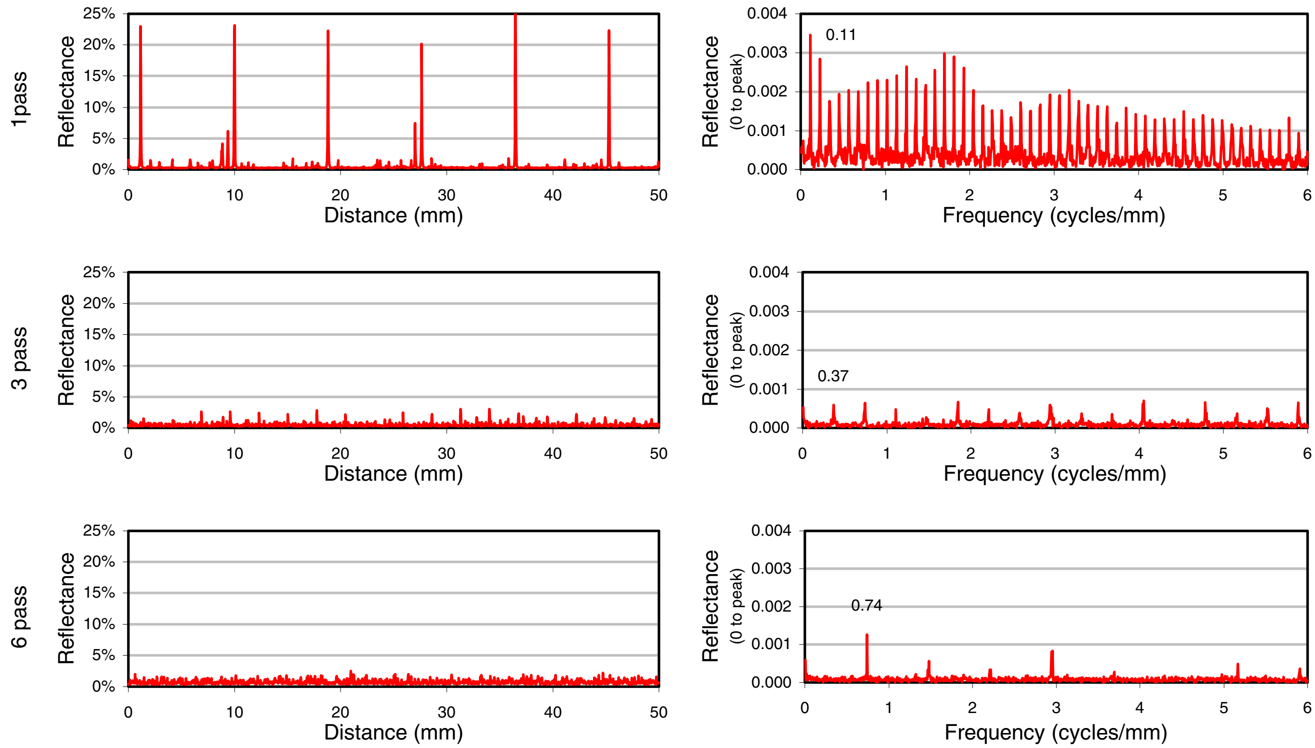


Figure 3: Banding graphs for the 70% black tint in 1 pass, 3 pass, and 6 pass mode. The graphs on the left are the reflectance profiles. The graphs on the right are the frequency domain plots.

At first glance, it is tempting to use the magnitude of the fundamental frequency (e.g. 0.113cyc/mm for 1 pass) as the metric for banding severity, but a closer look at the data shows this to be unreliable. This can probably be explained by the fact that the banding severity is not indicated by the fundamental peak alone, but by the sum of the fundamental peak and its harmonics. A complicating factor is that the fundamental peak and any given harmonic may be in phase (strengthening each other) or out of phase (weakening each other). Further investigation is needed to sort out these issues.

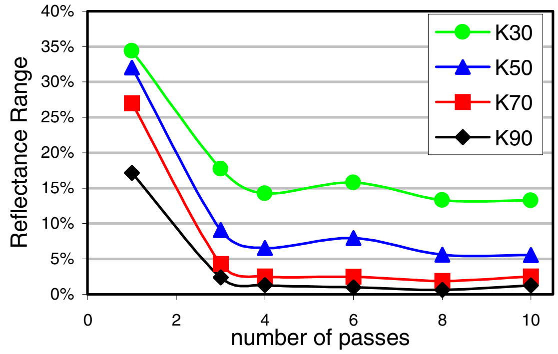
The reflectance profile offers two possible metrics, the *reflectance range* (max-min) and the standard deviation (*std*) of the reflectance profile data. Figure 4 shows the *reflectance ranges* and *std* for black only on the test samples. The data for the other colors show similar patterns.

If the reflectance variation shown in Figure 4 can be characterized as the “perceived band intensity,” it is clear to see that this perceived intensity decreases with the number of passes. There is a big drop in reflectance variation from 1 pass to 3 passes, followed by more gradual changes from 4 to 10 passes. The 6-pass mode shows some deviation from this trend, especially for the 30% and 50% black tint (K30 and K50 curves). This deviation is much more evident in the *reflectance range* data than in the *std* data. This suggests that the reason for the deviation is a single band in the 6-pass sample that is uncharacteristically light.

Thus, if *reflectance range* is used as a metric it must be kept in mind that it is sensitive to a single bad data point in the measurement or a single bad area on the sample. Another concern is that a *reflectance range* metric gives no weight to the width of a band. Bands 50µm wide and 100µm are rated the same if they have the same reflectance. Certainly this does not reflect the perceived relative severity of two such bands. Nevertheless, it is too soon to dismiss *reflectance range* as a potential tool for quantifying banding severity.

Standard deviation (*std*) has a number of advantages as a potential metric for banding. First of all, unlike *reflectance range*, *std* increases with increasing band width. Secondly, *std* is not as susceptible to isolated bad data points or bad spots on samples. Clearly, *std* needs further investigation as a possibility.

Figure 4 shows that *reflectance range* and *std* behaved similarly as banding metrics. Figure 4 also shows much higher *reflectance range* (and *std*) values for the 30% tint compared with the other curves. It is common experience in ink jet printing that the worst banding occurs in images of 30% to 50% print density, and our data seem to confirm this. But we must be cautious. We have not performed subjective studies to prove that these particular 30% samples are perceived to be worse than the 90% samples. It is possible that the variations in reflectance are due to halftone noise. It may also be that samples with higher overall reflectance such as the 30% tint have inherently higher *reflectance range* and *std* even if banding is not present. So caution is in order when comparing data from samples with significantly different average reflectance values.



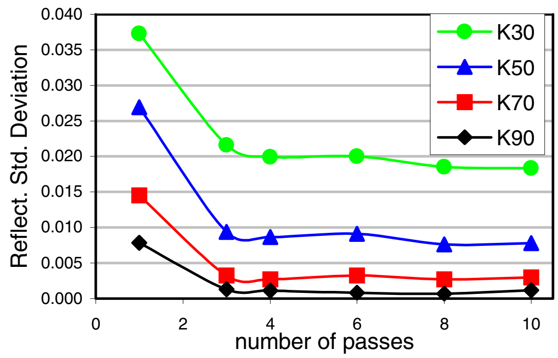


Figure 4: Statistical information on reflectance profiles for 30%, 50%, 70%, and 90% black tint.

From a practical standpoint, either *reflectance range* or *std* could be used to develop acceptance criteria for banding, as long as the same print densities were used consistently (e.g, if 50% black tint were always measured). Therefore, a banding metric could be developed that makes use of both. A mathematical expression could be developed from objective banding measurement data, such as the data shown in Figures 4 and 5, together with subjective preference data, capturing the correlation between the two. It must be kept in mind that a banding metric must take viewing distance into account. In addition, a number of variants of the metric may be required for different applications.

With the automated system used for this study, we have the ability to quantify the effects of the long-standing practice in ink jet printer design of using multiple passes to achieve better print quality. Given the capability of our system to generate large amounts of highly reliable data from these multi-pass print samples, it may now be possible for product developers to optimize the trade-off between speed and quality. The trick lies in figuring out what level of print quality is actually necessary. Much work remains to be done to be able to correlate what we *need* with what we can *measure*, but some important pieces are now in place for the development of a single metric with which all our banding questions can be answered.

Conclusion

In this paper we have shown that it is possible to objectively quantify the severity of banding using an automated measurement instrument. The technique was applied to quantifying the relationship between banding severity and the number of print passes used to generate ink jet prints. The technique showed that frequency analysis was useful for diagnosing the root cause of a banding problem. It was also found that the *reflectance range* (max-min) and *reflectance standard deviation* of the reflectance profiles were useful in quantifying the overall banding severity.

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Biography

Dr. John C. Briggs joined QEA in January 1998. He is responsible for new product development and pre-sales customer support. Previously at Iomega Corporation, he was a key contributor to the design and development of the Zip™ drive. Dr. Briggs holds eleven patents and has several patents pending. Between 1986 and 1991, he received his BS, MS, and Ph.D degrees in Mechanical Engineering from the Massachusetts Institute of Technology. His research focused primarily on non-destructive testing and acoustic emission measurements.