Imaging Considerations for Single-Pass Print System Design

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Abstract

The interest in single-pass inkjet printing has accelerated due to a number of key advantages over other architectures and technological approaches. These include significant increase in productivity over scanning based printing architectures, ability to print using a wide variety of ink types onto different media at high speeds, and image quality that meets or surpasses equivalent scanning based applications. However, these benefits come with significant system design considerations and challenges. Unlike a scanning printer where image quality is benefited by built-in redundancy, in single-pass printing, you don't get a second chance to make a good first impression. The design of a single-pass system must consider all possible variables that affect drop volume and drop placement. Drop placement is dependent on printhead characteristics like jet straightness, velocity uniformity, and alignment; combined with the accuracy of the substrate handling capability of the driving platform. There are potential ways to reduce such errors by properly architecting the system as a fully integrated unit. Important design considerations like interleave pattern between printing rows and proper spacing between these rows to reduce the overall footprint of the print zone can dramatically reduce these errors and thereby improve image quality. This paper investigates such errors quantitatively, how they correlate to system design and ways to address them in an integrated design approach. A variety of analytic and simulation tools used to understand effects on the single-pass image quality are described. Techniques to benchmark motion quality of a conventional printing press will also be discussed. By using these tools, a successful single-pass system can be designed that achieves target image quality requirements.

Introduction

Single-pass inkjet printing demands higher printhead performance and precise understanding of the target application requirements. A proper translation of printhead jetting characteristics to resultant drop placement on the substrate in ordinance with other system parameters is a critical exercise for successful system design. These considerations significantly focus the decision making process in determining the tradeoffs to be made in bridging the gap between performance specifications of a printhead and image quality requirements of the target application.

In a single-pass printhead, a number of jetting assemblies that have lower native resolution (aka nozzles per inch or 'npi') can be mechanically assembled to achieve higher system resolution. For example, four 100-npi jetting assemblies can be mechanically interleaved together to achieve 400-dpi printhead addressability. Also a number of these printheads can be stitched along the line of nozzles to achieve higher print widths. In other instances they can be stitched in the direction perpendicular to the line of nozzles resulting in more than one nozzle per line. This type of redundancy lowers average duty cycle of the printhead by lowering overall jetting frequency, a key benefit inherent to scanning printer designs. Image artifacts at the stitch line are particularly important as human vision is sensitive to spatial variations in image reflectance and edge profile. The following sections explore variables that affect single-pass printing and techniques to measure or even adjust these variables.

Drop Size Requirement

One of the most important decisions to be made early on in an inkjet system design is determining the target drop size that will provide required image quality for the target application. Large drops are preferable as they provide better area coverage and higher ink density, but at the expense of overall image resolution due to the larger spot size on substrate. Smaller drops provide higher image resolution, better image quality and lower detectability, but may lack in overall ink density and are more sensitive to placement errors. Figure 1a below shows the minimum spot size required for a 720x720dpi application. It is important to note that the illustrated spot size does not include any placement errors. The spot size diameter is equivalent to the pixel diagonal, and is calculated by multiplying pixel size by square root of 2. If all spots are similar in size and there is no placement error, it should provide 100% coverage. Figure 1b shows a row of spots offset by 25µ. This may be a result of single jet firing crooked or an entire jetting assembly mis-aligned within a printhead. As shown it can result in a 9µ gap for the given spot size. To compensate for this error, the drop size needs to be increased. In this case a drop size that results in 75µ spot size should cover this error as shown in Figure 1c.

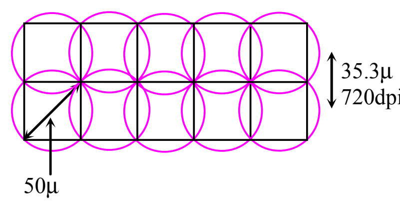

***Figure 1a**. Minimum spot diameter*

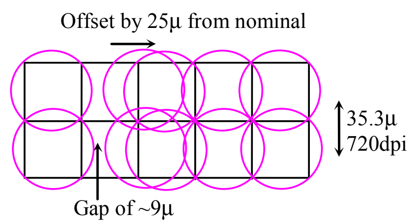

***Figure 1b**. Effect of 25µ drop placement error*

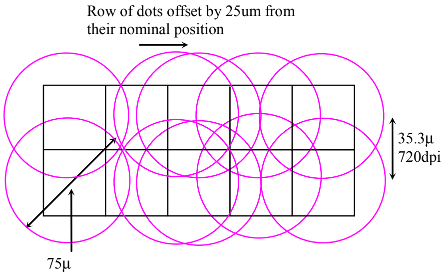

***Figure 1c**. Error compensation by increasing spot size*

An important frequently asked question is what drop size (measured either in mass or volume) results in what spot size. The answer is very clear, "it depends". There are a large number of variables that affect resultant spot size such as substrate type, ink type, surface coating, curing or drying method to name a few. Experiments to understand the relation between the drop size and the spot size need to be conducted. Once this is understood, a review of overall system design including potential error sources and resultant errors need to be considered before determining the required drop volume for an application.

Drop Placement

Drop placement plays an important role in determining the target drop size. It can be broadly divided into placement error in the direction of line of nozzles (X) and the direction perpendicular to the line of nozzle (Y). Both these errors scale linearly with standoff. Standoff is the gap between the printhead and the substrate. Errors can be minimized significantly by decreasing standoff distance. In the following sections potential sources that cause these errors along with the methods to quantify them, and their effect on the image quality are discussed.

Placement error in X

Drop placement error in X is crucial for single-pass printing as misplaced line of drops results in overlapping neighboring drops on one side while leaving a gap on the opposite side as shown in the examples above. From the image quality perspective this results in contrast banding and streaks, both of which are easily detectable. The primary sources for placement errors in X are jet straightness deviation, misaligned jetting assembly within a printhead, non-orthogonality of a printhead to the axis of substrate travel, and substrate meandering, commonly referred to as web weave. All these errors result in the placement error in X at variable degrees depending on the other system components like standoff, substrate speed, and motion accuracy. The drop placement error based on the jet straightness is straightforward to calculate using the following equation:

$DPE_x = S \ x \ \tan(\theta)$

where DPE_x is drop placement error in μ, S is standoff in μ, θ is angular jet straightness error in milliradians.

Drop placement error based on a misaligned jetting assembly is the same as the mechanical alignment error for the jetting assembly within printhead, and can be measured using optical inspection tools. Placement error based on a non-orthogonal head and web weave are more complicated to measure as they relate to substrate motion. This requires printing specific test images comprised of printed lines or spots using specific jets that can later be measured and translated to above errors. One method is to print lines using jets from interleaved jetting assemblies. These lines can be measured using a machine vision system for the line spacing based on their respective positions. Line position errors can then be calculated from the best fit line to these data. By studying the pattern of these errors, mechanical alignment error can be isolated from the error resulting from the printhead's non-orthogonality. Figures 2a to 2c illustrate three scenarios. The slope of the best fit line is a measure of the head orthogonality (or rotationality) error, and the offset of average head position error (shown as squares) from the best fit line represents the mechanical alignment error.

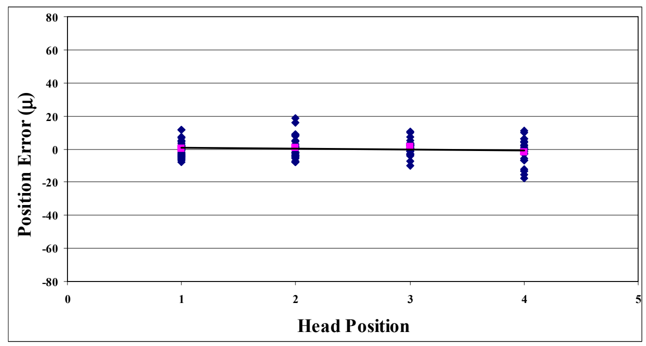

***Figure 2a**. Plot representing no head position error and no printhead rotationality error*

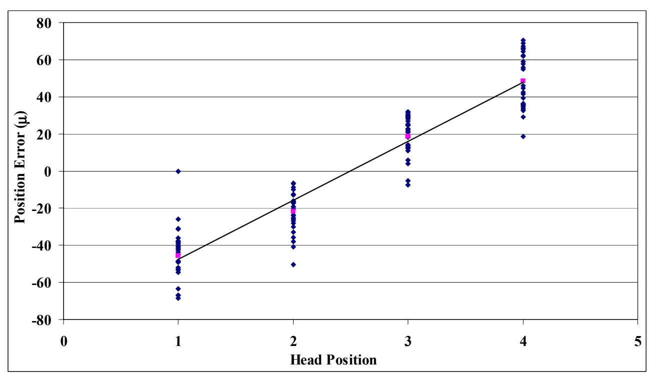

***Figure 2b**. Plot representing no head position error, but ~4µ/mm printhead rotationality error*

As shown in Figure 2a, neither error exists as the best fit line has zero slope, and it passes through average position error for each jetting assembly. Figure 2b exhibits the case with head rotationality error due to the slope of the best fit line, but no alignment error as the best fit line still passes through the average position errors. Figure 2c indicates the inverse of 2b. Here jetting assemblies 3 & 4 are mechanically misaligned, but the printhead doesn't have overall rotationality error.

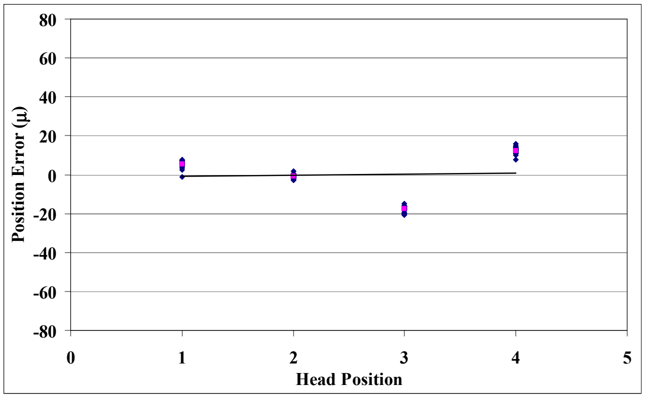

***Figure 2c**. Plot representing no head rotationality error, but -18µ and 12µ mechanical alignment error for heads 3 and 4*

The technique described above assumes the jets used to print this pattern have no or minimal straightness error, standoff to the substrate is uniform from one jetting assembly to another, and the web weave error is negligible or the width of the print zone is very small. This analysis works only if the magnitude of these errors is limited; otherwise the analysis can be skewed resulting in erroneous results. Position error spread for the individual jetting assembly is due to the jet straightness error, and by using their average in the analysis minimizes the calculation errors.

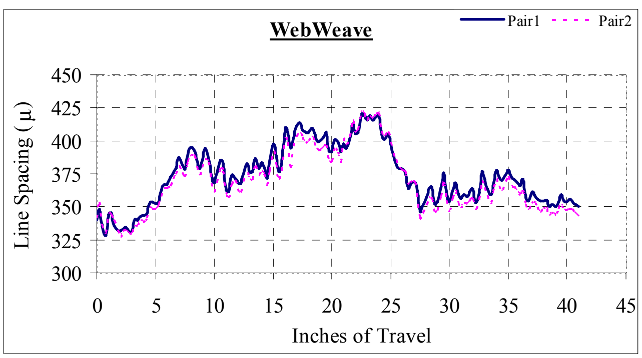

***Figure 3**. Web weave error over distance in Y*

Similar to the head alignment and the rotationality errors, web weave error can also result in images with streaks and/or banding. Web weave is associated with a system's motion quality and is quantifiable both mechanically and by printing test patterns. If measured using printed patterns, the simplest way to quantify it is by printing a series of parallel lines with jets from the jetting assemblies that interleave over the width of the print zone. The deviation in spacing (measured in X) between these line pairs, measured at short but regular intervals in Y, indicates the magnitude of the web weave error. Analysis can be performed on a number of line pairs for the measurement repeatability. Figure 3 shows spacing for two line pairs against the distance in Y. It is interesting to note that overall peak-to-peak variation in spacing is ~100µ over 40" distance in Y, but approximately 75µ drop in line spacing is observed at 25" over 5". This can result in significant error in drop placement in this region.

Placement error in Y

Contrary to the drop placement error in X, the placement error in Y typically doesn't result in streak or banding in the image. Rather, it affects edge acuity, and makes lines and text appear ragged or fuzzy. This can adversely affect the quality of fine text, reverse text and fine image features. It also results in the printhead registration error, for both monochrome and multi-color printing applications. A system's encoder inaccuracy, the printhead's velocity non-uniformity, and printhead alignment error in Y are major contributors that can result in the drop placement error in Y. Jet straightness is not a significant component as the human eye is more sensitive to spatial variation in edge profile than localized variation. Similar to the printing lines for web weave error analysis, the spots can be printed by interleaved jets to analyze the placement error in Y. As shown in Figure 4 below, the placement error in Y would account for encoder error, and the placement error in X would account for the web weave error. The first two cases represent no encoder and web weave errors as the spacing between spot pairs in both X and Y remains constant across the printing distance in Y. The third case is an example of both encoder and web weave errors due to the spacing varies in both X and Y. The spacing between spots can be measured using a high resolution machine vision system to analyze these errors.

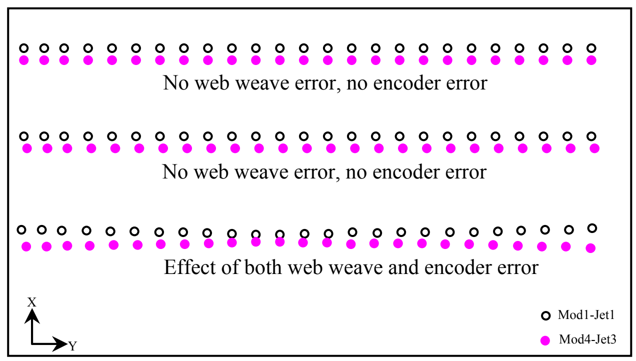

***Figure 4**. Analysis of drop placement error in X and Y*

Drop placement error associated with velocity uniformity is a function of printhead standoff, substrate speed and the delta velocity. Equation below represents the drop placement error based on the maximum velocity delta, and therefore the worst case drop placement error. A single jet velocity is typically not a concern as compared to a bank of jets firing at non-nominal velocity. A jetting assembly with a velocity profile that has systematic pattern can also result in unacceptable image quality.

$DPE_y = V_s \times S \times (1/V_1 - 1/V_2)$

where DPE_y is drop placement error in Y in µ, S is standoff in µ, V_s is substrate speed in m/s, V_1 is lower end jet velocity in m/s, V_2 is higher end jet velocity in m/s.

Image Simulation

FUJIFILM Dimatix has developed a tool called 'PrintSim' that assists image analysis by simulating single-pass images. PrintSim takes an input image; a head configuration file defining the head in terms of number of jetting assemblies, jets per assembly, jet spacing, and their interleave pattern; a screen file defining the threshold and the order for drops to be laid on the substrate; and error profiles representing drop placement and drop size errors. Basically, this tool draws spots with the user-specified dimensions at the user-specified locations. It is a useful tool to understand the potential effect on image quality based on a set of printhead and system parameters. For example, it can be used to do a simple analysis to find if a certain spot size is adequate for a 600x600dpi application to a more complicated analysis, like the effect of 5% velocity variability on the image quality. Once a simulation is performed, an image analysis tool can be used to perform analysis such as line width, edge raggedness, edge blurriness, and spot graininess. This analysis can be performed on an output simulated image in either electronic form or the image printed on paper at very high resolution to maintain spot size and placement fidelity.

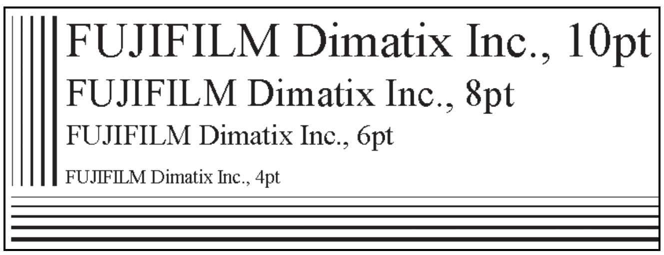

Figure 5a. Original 400x400dpi non-simulated .tif image

Table 1a. Analysis performed on 5 vertical lines in original non-simulated image (Figure 5a)

Count	5
Lead Blur (μ)	50.800
Trail Blur (μ)	50.800
Lead Ragged (μ)	0.000
Trail Ragged (μ)	0.000
Width (μ)	177.800
Distance (μ)	762.000

Figures 5a, b, & c illustrate how this image simulation can be used to determine whether the final image quality is acceptable. Figure 5a represents an unprocessed 400x400dpi tiff image. Table 1c shows analysis performed on 5 vertical lines in this image using image analysis tool. The data shows no edge raggedness, which is a measure of line roughness measured as standard deviation of the residuals of a line to its best fit line. A straight vertical line may have lower edge raggedness than a line that is rough along the vertical edge. As described above, edge raggedness results from the drop placement error in Y due to either encoder inaccuracy or drop velocity non-uniformity. As expected, the input image does not have any edge raggedness.

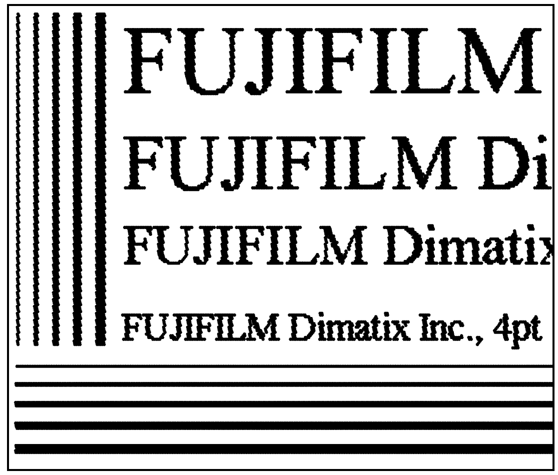

Figure 5b. Simulated image with 3mm head spacing

Table 1b. Analysis performed on 5 vertical lines in Figure 5b

Count	5
Lead Blur (μ)	8.000
Trail Blur (μ)	8.000
Lead Ragged (μ)	14.897
Trail Ragged (μ)	17.485
Width (μ)	248.964
Distance (μ)	761.843

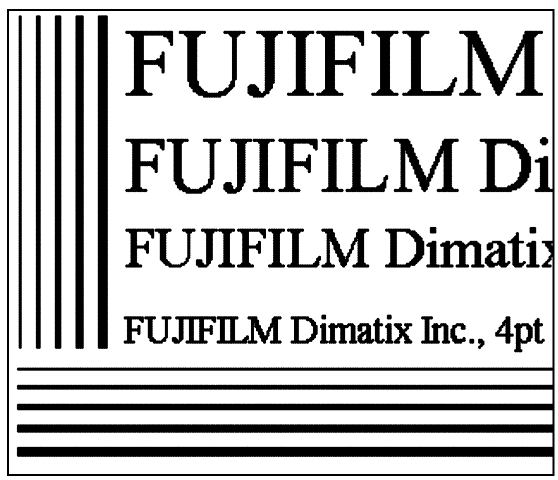

Figure 5c. Simulated image with 5mm head spacing

Table 1c. Analysis performed on 5 vertical lines in Figure 5c

Count	5
Lead Blur (μ)	8.000
Trail Blur (μ)	8.000
Lead Ragged (μ)	3.618
Trail Ragged (μ)	3.443
Width (μ)	239.159
Distance (μ)	762.244

Figure 5b represents the same image simulation using 120µ spot size and an HCF file that represents four 100-dpi interlaced heads that are spaced 3mm in the Y direction. This test is performed to understand the effect of ratio of head spacing to pixel size in Y on the edge acuity. In this case the ratio of head spacing (3mm) to 400-dpi pixel (63.5µ) is not an integer number, which means there will be placement error between drops jetted by different printheads within the assembly as a result of system design. The magnitude of this error as measured in edge raggedness is approximately 15µ on the leading edge and 17µ on the trailing edge. For some high resolution applications, this error may be unacceptable. It is important to note that this error, besides the incorrect head spacing, also includes error due to circularity of the spots. If spots were printed square, representing cubical drops in flight, it would result in lower edge raggedness. Also in reality, jetted ink drops spread on the substrate and merge with neighboring drops, which can result in a different scenario than perfectly circular spots marked on the substrate by PrintSim. Figure 5c represents the simulated image using head spacing of 5mm, which results in an integer head spacing to pixel size ratio. As shown, the edge raggedness is significantly decreased with this change in the printhead alignment design.

Conclusion

A number of image quality aspects of single-pass inkjet printing were discussed along with the system design considerations that can be determined in advance that if met can satisfy target application requirements. A brief overview of the inkjet simulation tool was also given with the examples that demonstrate its capability in understanding the effect of system parameters on overall image quality.

Author Biography

Saurabh Halwawala joined Fujifilm Dimatix, Inc., in 2001 as an Image Quality engineer. He is responsible for developing imaging tests designed to understand and evaluate performance of Dimatix printheads. His task is to translate marketing requirements to print specifications, and develop imaging strategies for Dimatix products to achieve those application requirements. Saurabh holds an M.S. (2000) degree in Paper, Printing and Imaging Science and Engineering from Western Michigan University, Kalamazoo, MI; and a B.S. (1998) degree in Polymer Technology from L. D. College of Engineering, Ahmedabad, India.