Imaging Models for Robust Single-pass Printing using SAMBA™ Piezo Drop-on-Demand Silicon MEMS (Si-MEMS) Inkjet Printheads

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Abstract

SAMBA™ inkjet printheads offer a high nozzle packing density of 1200 nozzles per inch, flexibility to print with multiple drop sizes, and wide ink latitude making them attractive candidates for a variety of inkjet printing applications. In this paper, we offer insight into how these features can be utilized to enable imaging models that provide high image resolution and print speed as well as increased robustness to missing jets, a key element required in single pass printing. We show that SAMBA printheads can be designed to operate in multiple imaging modes and we use simulation and experimental data to analyze their performance. We evaluate multiple imaging models enabled by SAMBA 1200 printheads and compare them for their image quality capability, image artifacts caused by transient jets, and productivity potential for single pass printing. We show that Samba 1200 imaging models combined with over-addressing and grayscale printing offer superior image quality and improved robustness to streaks without compromising on productivity.

Introduction

SAMBA technology is a ground-breaking silicon MEMS inkjet printhead technology developed by FUJIFILM Dimatix that has the potential packing density and cost of Thermal Ink Jet (TIJ), combined with the high throughput of Continuous Ink Jet (CIJ) while providing the operational flexibility associated with Piezo Ink Jet (PIJ). This technology is a quantum leap forward that redefines how Piezo DOD inkjet technology can be designed, manufactured, and applied. SAMBA printheads mark the first comprehensive Piezo DOD inkjet platform that truly delivers on the promise of wide-width, high resolution, single pass, drop-on-demand inkjet printing in an elegant, compact form [1].

The SAMBA family of printheads is fabricated using some of the most advanced silicon micro-machining processes and therefore is able to integrate multiple functionalities in a very small foot-print. These functionalities include a two-dimensional precision nozzle array etched in silicon enabling high nozzle density and exceptional jet straightness, a compact network of ink channels to provide a continuous ink recirculation around the nozzles for reliable jetting and high firing frequencies, a high performance pumping chamber with sputtered PZT film actuator [2] on a thin silicon membrane offering high uniformity and precision control over drop volume and drop velocity, as well as a durable non-wetting coating for high reliability and ease of maintenance. An important structural feature of SAMBA jet design is elimination of PZT material from the path of often-aggressive jetting fluids while overcoming the source of mechanical crosstalk inherent in shared wall designs. The Si-MEMS technology used to fabricate SAMBA printheads incorporates the PZT onto a thin barrier layer atop the ink channel to form the pumping chamber. In this way, the entire micro-array is fabricated as a single silicon monolithic structure. This results in a highly efficient high-resonant-frequency jet design with no contact between the jetted material and the PZT. This unique drop ejector design of SAMBA printhead enables drop volumes ranging from less than 1 pL to 30 pL and is capable of ejecting fluids of viscosities in the range of 3-12 cP. This is achieved by a wide jet design space combined with powerful VersaDrop™ [3] multi-pulsing jetting capability that enables creating multiple drop sizes up to six times that of the native drop volume. An additional attractive feature of the SAMBA jet design is its very flat frequency response enabling high drop ejection rates, small drop volumes, and precision drop placement. In addition to the precision microfabrication enabled by Si-MEMS technology, all silicon construction also offers excellent resistance to mechanical abrasion, tolerance to high temperatures, and robustness to chemical attack. Thus, SAMBA printheads are compatible with a wide range of inks including aqueous (dye based and pigmented), UV, aqueous-UV, latex, and solvent-based inks.

***Figure 1**. A single SAMBA print module*

Figure 1 shows an image of a single SAMBA print module. SAMBA printheads are designed to be highly scalable to enable many individual print modules to be aligned to form a single, tightly integrated printbar . Printbars can be varied in both length and resolution to accommodate industry standard press sizes serving diverse printing applications from multi-page signatures to traditionally analog applications.

The performance and versatility of SAMBA printheads make them ideal candidates for wide ranging printing applications including commercial printing, textile, label printing, and packaging. Many of these applications require single-pass operation to meet the high throughput requirements. One major challenge in achieving long-term robust operation in single-pass inkjet printing is the presence of occasional transient missing or severely misdirected jets For example, in certain applications, defective jets are identified and disabled to prevent printhead failures and therefore are not available to eject drops. In scanning mode printing, such disabled jets do not cause significant print artifacts as several jets scan a particular area on the image. However, in single pass printing mode, transient missing or disabled jets often cause visible artifacts on the printed images such as streaks. Thus, it is necessary to design imaging strategies that are tolerant to a small number of isolated defective jets for extending printhead lifetime and lowering total cost. One common and effective solution to reduce streaks due to missing jets is to use multiple printheads in process direction to create redundancy. This is often expensive and requires larger footprint which is not possible in all applications. Alternatively, it has also been shown that neighboring jets with larger drop volumes can be used to compensate for defective jets for single pass commercial printing applications [4]. Such dynamic compensation techniques utilize real time detection of location of missing jets, smart imaging algorithms, and drop volume control using grayscale printing. Here, we investigate possibility of improving single-pass printing streak robustness via SAMBA 1200 imaging models in the absence of active compensation from adjacent jets by using optimized dot gain and image processing.

Imaging Models

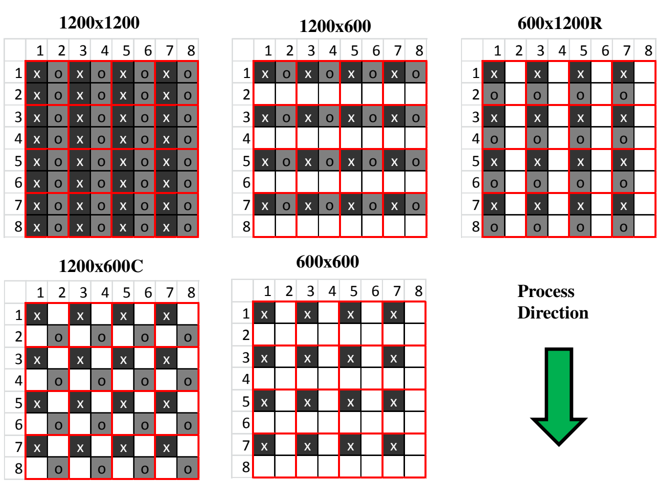

Figure 2. Imaging models compared in this paper. x and o represent pixels addressed by two equivalent 600 DPI arrays. 1200x1200 grid is shown in black color and 600x600 grid shown in red color. R=Redundancy or adjacent pixels in process direction addressed by two separate nozzles. C=Checkerboard or adjacent pixels in process direction also shifted in cross process direction.

In general, robustness to missing jets in single-pass printing is affected by many factors including image resolution, RIP, nozzle redundancy, printed dot size and shape, adjacent dot overlap etc. Additionally, there are application specific factors including image type and content, dot placement accuracy, dot size uniformity, density gradients within single dots, ink-substrate interaction etc. In this paper, we focus on imaging models enabled by 1200 nozzles per inch (NPI) SAMBA printheads or SAMBA1200. One of the key enabling features of SAMBA printheads is high native resolution of 1200 NPI arranged in a small form factor. This is achieved by a unique two dimensional matrix based nozzle arrangement designed for ease of stitching of multiple modules.

This high nozzle packing density offers a compact printhead that is essentially equivalent to two 600 nozzles per inch arrays. The matrix nozzle arrangement is flexible, so that the two 600 NPI arrays can be arranged to create either 1200x1200 DPI images on substrate or to create redundancy or checkerboard patterns by changing the arrangement of nozzles in the in the two dimensional nozzle matrix. Further, SAMBA printheads enable drop volumes that are appropriate for a range of image resolutions. This is enabled by a wide design space offering a variety of native drop sizes as well as multi-pulsing capability to create larger drops by combining several native drops. The flexibility in generating desired drop volumes allows SAMBA printheads to be used to create optimal dot gains for high image quality and robustness. Grayscale printing capability adds a third dimension to capability of SAMBA printheads to further improve image quality by achieving desired granularity and optical density. To study the potential of SAMBA technology to offer high image quality and robustness, we evaluated different imaging models enabled by SAMBA architecture, namely 1200x1200, 1200x600, 1200x600 checkerboard, 600x1200 redundant and compared them with the standard 600x600 DPI model with no redundancy. These models are shown in Figure 2. Here, process direction is from top to bottom and 'x' and 'o' represent pixels addressed by two sets of 600 NPI nozzle arrays in the SAMBA printhead. When a single pixel in 600 DPI grid is addressed by two separate nozzles, we achieve a level of redundancy in case one of the two nozzles is defective. Additionally, the different imaging models represent variations in the arrangement of pixels in 1200 DPI grid. 1200x1200 imaging model offers high image quality, while 1200x600, 600x1200R and 1200x600C models enable twice the maximum process speed for the same maximum jetting frequency. To illustrate these further, dot patterns corresponding to imaging models of 1200x1200 and 1200x600 checkerboard printing are shown in Figure 3.

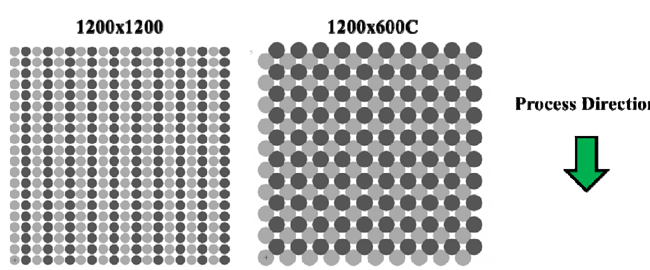

***Figure 3.** Example dot patterns for 1200x1200 and 1200x600C imaging models. ● and ● indicate dots created by two interlaced 600 NPI nozzle arrays that make the 1200 NPI SAMBA printhead.*

Analysis

To evaluate SAMBA imaging models for their robustness and image quality, we created simple plots of random stochastic patterns of dots under ideal conditions. Note that these patterns are only for the illustration purpose and are not carefully designed half tones. Also, only one dot size is used in each block. The dots are assumed to have perfectly round shape, a uniform color density and are placed without any position or size errors.

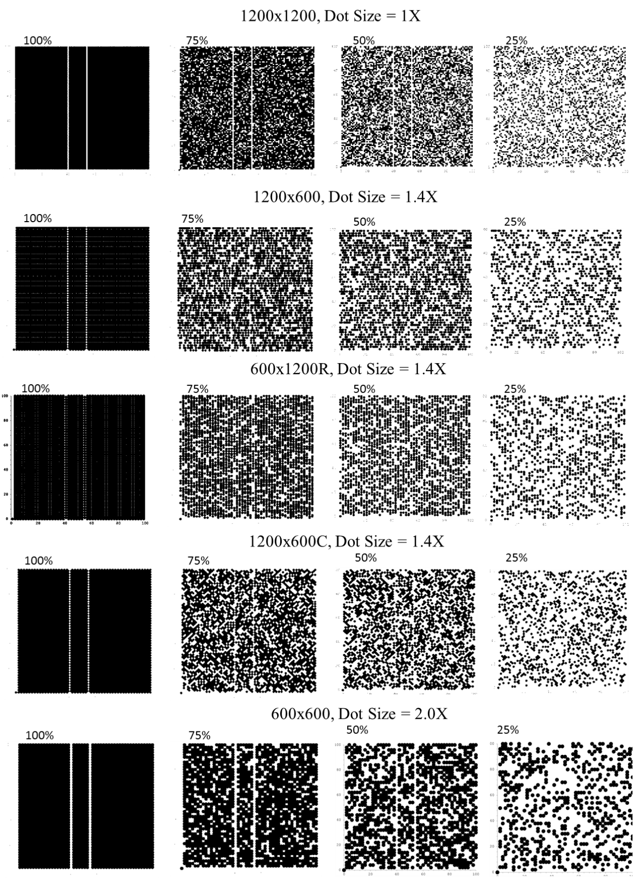

***Figure 4**. Example ideal stochastic print dot patterns with 100% and 75% coverage for different image resolutions and two missing jets. Dot size for 1200x1200 image is selected to cover a square pixel diagonally while that for 1200x600, 600x1200 and 1200x600C models is 1.4 times the dot size 1200x1200.*

For example, in Figure 4, we show 100x100 pixel blocks with two simulated defective jets each that are disabled. The print direction is from top to bottom. The dot size used for the imaging model comparison is dependent on the ink coverage needed to achieve 100% fill. For example, 1X is the dot size required to fill 1200x1200 DPI cell along diagonal. As 1200x600, 600x1200R, and 1200x600C models shown in Figure 4 have less number of dots corresponding to the lower image resolution, these require 1.4X dot size to achieve similar ink coverage. Similarly, 600x600 DPI model is plotted with 2X dot size. As expected, the smaller dot size enables better granularity (and sharpness) and therefore a higher image quality. Also, for the selected dot sizes 1200x600 and 600x1200R imaging models are more susceptible for gaps between dots while the 1200x600C model shows better coverage because of the adjacent dots overlap. In all models, streaks caused by missing jets are visible, especially in higher ink laydown areas. However, the intensity of streaks is less compared to streaks in an equivalent 600x600 imaging model. This is because the larger dot size is required to fill 600x600DPI grid and only one nozzle is addressing an entire line in the vertical direction. On the other hand 1200 DPI models have 2 nozzles addressing one 600 DPI pixel and therefore offer a level of redundancy and therefore improvement to streak robustness compared to 600x600 DPI no redundancy model. We varied dot size for each imaging model to find suitable size to hide streaks and studied its effect on image quality. For example, we evaluated the possibility of using larger than nominal drop volumes to create a larger overlap of adjacent dots. Figure 5 shows dot patterns for SAMBA 1200 imaging models when larger dot gain is used to hide the streaks caused by missing jets. It is clear that a larger dot size can further reduce streaks created by missing jets at the cost of granularity, especially at lower fill percentages. One solution to overcome this problem is through the use of the SAMBA printhead's of grayscale capability to select dot size based on local image density.

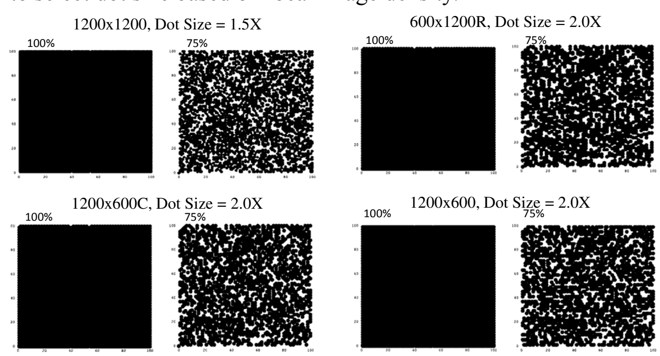

***Figure 5**. Example stochastic print dot patterns with two missing jets for 1200x1200, 600x1200R, 1200x600C, and 1200x600 imaging models and ink coverage for two different fill factors.*

For example, in Figure 6, for imaging model 1200x600C, larger dot size (2.0X) is used for darker areas while smaller dot size (1.4X) is used for light areas. Note that factors such as jet directionality errors, drop volume variations, density gradients within dots, ink mobility on substrate, ink substrate interaction play a significant role in image quality as well as robustness were not taken into account in plots shown in Figures 4, 5 and 6. These factors will likely affect the actual streak robustness compared to one shown here.

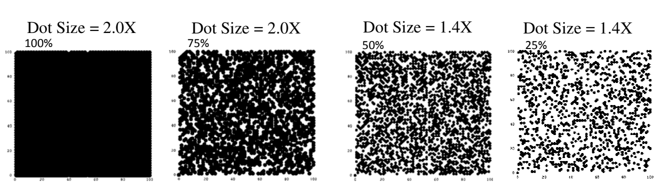

***Figure 6**. Example stochastic print dot patterns for 1200x600C imaging model and 100%, 75%, 50% and 25% ink coverage using two dot size to improve granularity in lower tones while improving streak robustness at higher fills factors.*

Results

To validate the analysis presented in the previous section, we created simple patterns at various fill factors in terms of percentage of pixels printed. We used a variety of substrates giving different dot sizes, dot ink densities, and gloss/matte finish. The patterns included 100x100 pixel blocks. All tests were performed using a black pigmented aqueous ink. We used different waveforms from 1 pulse to 6 pulses giving drop volumes that ranged from 1.75 pL to 11.0 pL. All prints were made at 8.3 inch/s linear print speed or at 10 kHz of jetting frequency. The drop velocity was in the range of 8 to 9 m/s and the stand-off from nozzles to substrate was approximately 1 mm. Figure 7 shows sample results on a gloss substrate. The images are magnified to show the details and each square block is 100 pixel wide 1200 DPI grid (2117 um). 100% and 70% refer to the percentages of total number of pixels printed in stochastic pattern. Here, a 1 pulse waveform giving a 32 µm dot size was used for the 1200x1200 resolution, a 3 pulse waveform giving a 45 µm dot size was used for the 1200x600, 600x1200R and 1200x600C resolutions and a 6 pulse waveform giving a 59 µm dot size was used for the 600x600 baseline resolution. These sizes approximately correspond to those in Figure 4. A comparison of results shown in Figure 7 and predictions made in Figure 4 yields similar trends.

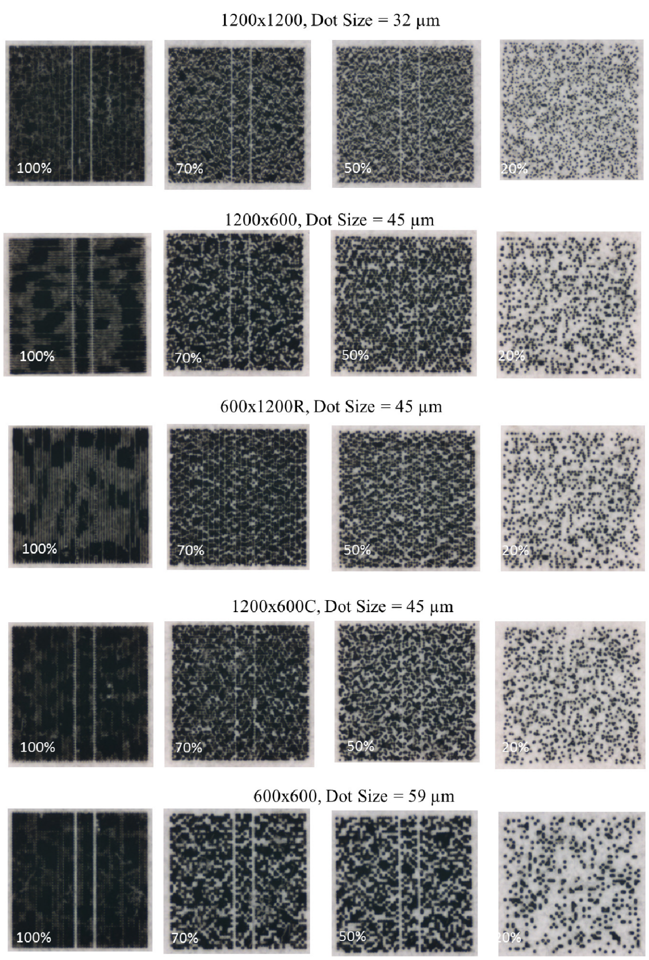

***Figure 7**. Sample printed dot patterns for two different fill factors for various imaging models with 2 jets disabled.*

Although streaks due to missing jets are visible in all models, generally, streaks are more visible in higher fill factor areas as predicted. 1200 DPI models show improvement over baseline model - 600 DPI model with no redundancy. The streaks caused by the missing jets in 600x1200R model appear to be the least visible among 1200 DPI models making it an attractive candidate. On the other hand, for the selected dot sizes, 600x1200R and 1200x600 models show vertical and horizontal striations as predicted. Comparatively, 1200x1200 and 1200x600C models show better substrate coverage and less mottle.

It is important to note that, the gloss substrate results shown in Figure 7 highlight the streaks created by missing jets. Other substrates yielded varying streak visibility depending on dot size, shape, and other ink-substrate interactions. Depending on the ink, substrate, dot size, printed dot pattern, and application, these streaks may be sufficiently invisible under normal viewing distance that these would be acceptable without any over-addressing schemes or compensation from neighboring jets.

Figure 8 shows sample print patterns for the 1200x600C model on gloss and matte substrates having different dot sizes. As expected, higher dot size, improves missing jet streak defect visibility. In addition, ink-substrate interaction also plays a critical role in determining the streak size. This is likely the cause for the streaks in print samples shown in Figure 8 and are generally more pronounced compared to the model predictions in Figure 5. Also, as expected, increasing dot size negatively affects the granularity and sharpness and there is a trade-off between the robustness and image quality. As shown in Figure 6, it is possible to select different dot sizes to improve granularity at lower fill factors. Note that the sample results shown illustrate how different combinations of imaging models, dot gain, ink-substrate choice, image processing, and other factors affect image quality and streak robustness. In addition, many other parameters need to be studied in detail for determining a suitable imaging model for a particular single-pass application including robustness to drop volume variability, dot placement errors, quantitative assessment of graininess and mottle, edge raggedness etc. Usually, a trade-off between cost, productivity, versatility, image quality, and robustness is needed in leading to the appropriate choice of imaging model.

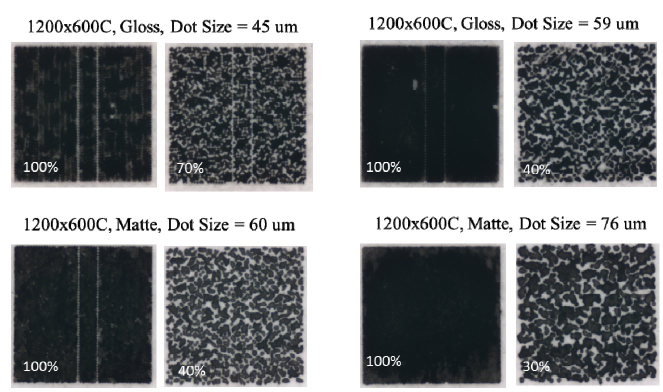

***Figure 8**. Sample printed dot patterns for different values of fill factors, dot sizes and substrates for various 1200x600C checkerboard model with 2 jets disabled.*

Conclusions

In this paper, we have discussed key enabling features of SAMBA printheads including high packing density of 1200 NPI and various imaging models enabled by the same. We offer insight into how these imaging models can be used combined with grayscale capability, and over-addressing to improve print image quality, streak robustness, and productivity. We presented preliminary data on simplified dot patterns with missing jets for various imaging models and compared predictions to a sample print data to support our hypothesis. The data suggests that SAMBA 1200 imaging models combined with over-addressing in high fill areas will help in reducing streak visibility due to isolated missing jets. The next steps include applying the techniques proposed in the paper to a variety of inkjet printing applications requiring different ink types and substrates to map out their effectiveness to meet desired image quality and streak robustness targets.

References

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Author Biography

Hrishikesh V. Panchawagh holds a Ph.D. in Mechanical Engineering from University of Colorado at Boulder (2006) and has extensive experience in research and development in areas of inkjet printing, Microfluidics, MEMS actuators, optical MEMS, MEMS displays, and BioMEMS. He has co-authored over 20 articles in internationally recognized journals and conferences and his research has led to more than 30 US and international patent applications including 8 issued US patents. He is currently a part of Applications Engineering team focused on SAMBA printheads at FUJIFILM Dimatix .

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 role is to help 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. Currently he is working as Printhead Applications Engineer at FUJIFILM Dimatix, Inc.

