Journal of Imaging Science and Technology® 51(6): 514–519, 2007.

Novel Image Trimming Algorithm for Use with Ink Jet Printing Fabrication[1]

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Abstract. *For the development of new ink jet printing (IJP) technology, instead of traditional processes, such as spinning, screen printing, photolithography, and laser printing, used for semiconductor and display fields, what are the obstacles to mass production? IJP is an ideal technology for fabricating material layering on a specific substrate that needs to be patterned. However, the line width presence often conflicts with the thin film requirement, i.e., to obtain a better line edge quality, the overlap distance of drops needs to be tuned closer and this results in greater thickness, which deteriorates the electronic performance. Besides, sometimes the image resolution for a metal circuit will be expected to fall within a tunable region, up to ±3 μm for a high level IC carrier board, in order to correct the image deterioration caused during the prior layering process. Those process needs are hard to achieve because of the innate characteristics of IJP transfer into the raster image data format. This paper proposes a novel image trimming method to transfer an original image to a trimmed image, based on the spreading factor between the liquid-solid interface and the assumption of linear superposition for drop-to-drop overlapping, as well as a versatile filtering function built-in as an auxiliary look-up table to modulate layer thickness. In detail, the trimming method included the procedure of pattern identification and location, image separation, seamless image merging, image boundary compensation, image trimming on spreading factor, and image reconstruction. The filtering method included the local characteristic of boundary inspection with a defined correcting function and varied filtering pattern applied to the inner field of boundary. The test pattern found that the circuit was satisfactory in terms of thickness and line width, according to expectation. © 2007 Society for Imaging Science and Technology.*
[DOI: 10.2352/J.ImagingSci.Technol.(2007)51:6(514)]

INTRODUCTION

Ink jet printing (IJP) technology has many advantages over traditional processes of mask-pattern fabrication, such as material saving and nimble pattern variation, but the upgrading from traditional processes to the IJP process has some obstacles to overcome. In the photolithography process, the standard protocol is Gerber RS274X for processing the conventional PCB Gerber format that belongs to description languages used for plotting the lithography mask aligner; the mask size for modulation of line width is simply adjusted by scaling the image data. For example, the metal circuit should be tunable in resolution up to ±3 μm for a high level integrated circuit (IC) carrier board to correct the image deterioration. However, the innate characteristics of IJP technology transfer the raster image data format and restrict its development because the resolution is nontunable with such fine resolution.[1] What is required is drop-to-drop overlap with ultraaccuracy, which results in the need to construct a huge bitmap, the impact of which will be the overloading of the system memory and CPU. Besides, high density of drop overlap will increase the layer thickness and spread the line width synchronously, compared to raw printing data. The printing process will be uncontrollable, in terms of material diffusion, and will lead to unexpected results, such as line overlap, plugged holes, pattern position shift, etc.

This article proposes the concept of modifying the raw printing data to reduce data format-converting mismatch and to constrain the increasing layer thickness and spreading of the line width, by trimming the original raw printing bitmap. This trimming method includes the procedure of pattern identification and locating, image separation, seamless image merging, image boundary compensation, image trimming based on a spreading factor, and image reconstruction; the filtering method includes the local characteristic of boundary inspection with defined correcting function and varied filtering pattern applied to the inner field of boundary.

IMAGE TRIMMING METHODOLOGY

Generally, image data compressed in a certain format cannot be used directly for ink jet printing. It first needs to be converted to matrix format, for example, BMP or TIFF image formats in common use, but the difficulty is that resolution loss occurs during format transfer. The disadvantage of BMP format is that it needs greater storage space, although it is easier to deal with in terms of data reading, compared to the TIFF format. To date, most industrial standards have adopted description language, such as the Gerber format; the transformation barrier between the Gerber and matrix formats requires a resampling process, and this entails resolution loss.

Even if the data transfer from analog (Gerber format) to digital (Matrix format) procedure were perfect, with no loss incurred, and if it were used for ink jet printing, insofar as an original image just defines the landing position for each dot, different behavior and printing quality would obtain for

[1]Presented in part at the IS&T Digital Fabrication Processes Conference, Denver, CO, September 17–22, 2006.

Received Mar. 13, 2007; accepted for publication Jun. 20, 2007.
1062-3701/2007/51(6)/514/6/$20.00.

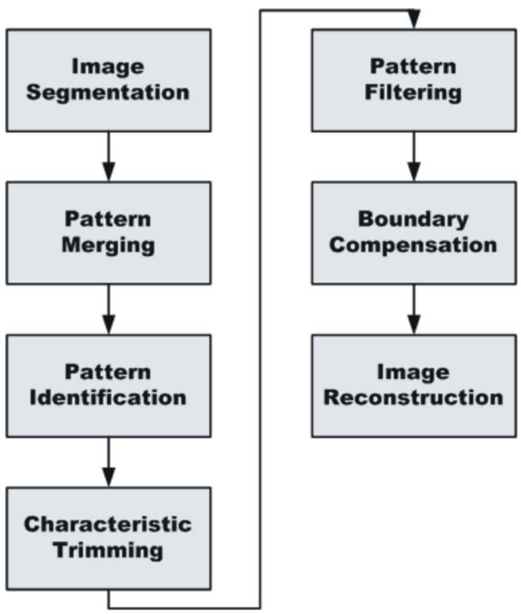

Figure 1. Flowchart for ink jet printing an image.

different substrate surfaces owing to wettability concerns. Wettability will cause the printed pattern to differ from the original, especially at the line widths and thicknesses required for IC applications. Therefore, a compensation scheme is proposed here to solve this problem, as described in Figure 1.

As an example, a printing region of 20 in. $\times$ 24 in. with 800 dpi resolution will generate a 16,000 pixel $\times$ 19,200 pixel image, which is a huge amount of data for image processing; thus preprocessing by image segmentation is needed.[2] This segmentation needs to be related to the requirements of the print head nozzles in order to enable the swath-printing process. The more detailed image will be sliced into 128 pixel $\times$ 19,200 subimage pixel strips for a full usage of 128 print head nozzles.

After image segmentation, some characteristic subpatterns will be degraded and may be hard to compare to the template to be identified (for example, a circle may to be segmented into semicircles). The pattern merge step is implemented to detect the pixel connectivity with the adjoining image and identify subpattern characteristics. With this connectivity operation, a pixel belongs to a pattern characteristic if it is located a distance of D (distance between pixels in horizontal or vertical direction) or $2.5D$ (distance between pixels in diagonal direction) from an adjacent pixel. Such a grouping of pixels is referred to as a characteristic cluster, consisting of the contiguous region of nonzero pixels. In this application, it is necessary to undertake a pixel-by-pixel comparison of the same characteristic field obtained at different image locations to correct for the relative translational shift magnification differences and rotational shifts, as well as geometrical and intensity distortions within images. Therefore, in the pattern merge step, the algorithm is: (a) to identify a certain characteristic cluster in a segmented image, (b) to find all the pixels that have connectivity with this characteristic cluster in this segmented image. (c) to find extra pixels connected with said characteristic cluster in adjacent segmented images, and (d) iteration of (a)–(c), to collect all connected pixels within a characteristic cluster (not on the same segmented image). After operations (a)–(d) operations, all the connected pixels separated at different segmented image should have been identified.

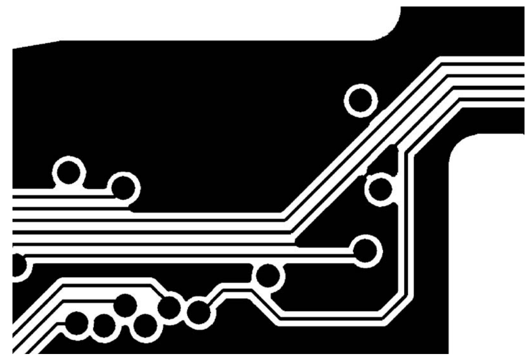

Figure 2. Image pattern example of a printed circuit board.

The completed characteristic cluster is then compared to the predetermined characteristic template.[3–5] called the pattern matching step. Pattern matching finds template matches regardless of poor lighting, blur, noise, shifting, or rotation of the template. Traditional pattern matching, such as the normalized cross-correlation, pyramidal matching, and scale invariant matching, have their limitations: time intensity and inaccuracy of characteristic identification. In this article, we operate with a new method to try to incorporate image understanding techniques to interpret the template information; this is an image processing technique that generates information about the features of a template image. It includes the geometric modeling of an image, efficient nonuniform sampling of an image, and extraction of template information that is rotation and scale independent. This technique reduces the amount of information needed to fully characterize an image or pattern and speed up the searching and comparing processes.[6] As an example, Figure 2 shows a portion of a printed circuit board that exhibits characteristics, such as circular, horizontal, slant, and vertical lines, etc., which should be identified.[7] However, in general, a template image is rarely an exact match because of image quantization effects on its shape, scale, and background noise. Consequently, a common procedure is to extract amplitude difference between the template and the image field at all points of the image field, and then to designate a detected characteristic wherever the difference is smaller than some established threshold level.[8]

Although the characteristic patterns have been identified, the challenge is in finding how to transfer the pattern exactly by ink jet printing onto a substrate. Generally, to inscribe a pattern with ink jet printing, the resolution loss is due to the matrix data format, or to the wetting or bleeding behavior due to the ink-substrate interface energy. For example, an expected circular pattern can be approximated by ink jet printing with fine drop and high density drop overlapping, but this procedure will cause fluid wetting over the substrate and unexpected wider or lower resolution in the

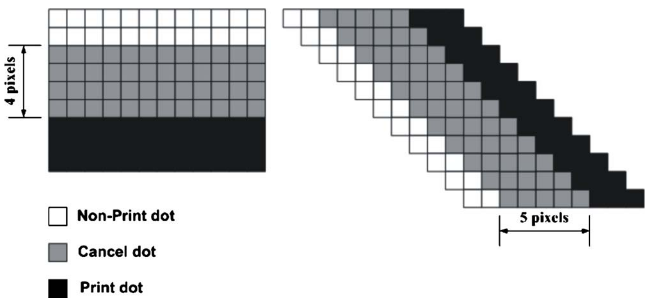

Figure 3. Trimming strategy depends on the characteristic pattern to keep same printing quality.

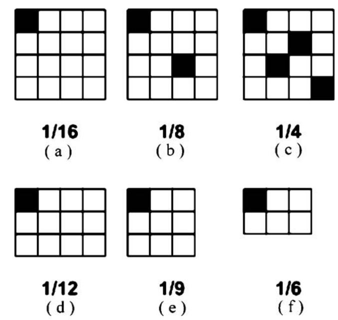

Figure 4. Cluster skeleton examples used for thickness modulation: (a) 4×4 space filter, filtering ratio is in 1/16; (b) 4×4 space filter, filtering ratio is in 1/8; (c) 4×4 space filter, filtering ratio is in 1/4; (d) 4×3 space filter, filtering ratio is in 1/12; (e) 3×3 space filter, filtering ratio is in 1/9; and (f) 3×2 space filter, filtering ratio is in 1/6.

pattern will result. Therefore, we implement the image trimming procedure before ink jet printing to correct for this inconsistency. The first step employs a Canny filter[9] to enhance the characteristic edge pattern information. This algorithm will provide the gradient magnitude and direction information along the edge. An edge is a significant change in the gray scale values between adjacent pixels in an image. Here, it is specially pointed out that the trimming methodology differs according to different characteristics. For example, a slanted line characteristic will aim to detect the edge along a ±45° direction, and a circle (hollow or solid) will compare the remaining tolerance by $r-\theta$ scanning with a default circle pattern.

The second step in image trimming is to correct for the inconsistency between the original and printed images due to the wetting spread of jetting materials on the substrate. The methodology is to reduce the contiguous pixels for certain characteristic patterns in an original image according to the wetting spread function of the substrate, by a typical scheme, such as eroding. Then the trimmed characteristic pattern will be jetted onto the substrate, with characteristic pattern dilation due to fluid wetting. If the spreading situation can be balanced with pixel eroding, then an exact pattern dimension can be realized in ink jet printing.[10] The key is that the spreading factor for the ink-substrate interface, the drop volume, and the desired printing resolution (or call it overlap of dot density) should be kept carefully consistent with the pattern trimming eroding percentage, called the trimming ratio (defined as the ratio of the pixels to the number of the original pixels to be printed, i.e., 0% for no trimming and 100% where all the characteristic pattern pixels are eliminated). Moreover, the trimming ratio for each characteristic pattern is different due to the different wetting direction (a vertical line will be trimmed in a horizontal direction and a horizontal line will be trimmed in a vertical direction) and coordinate transfer needed (circle pattern needing transfer from $X-Y$ into $r-\theta$ coordinate). Therefore, it is necessary to have an individual trim procedure for each characteristic. For example, suppose a drop landing on the substrate with 80 μm diam in 10 μm overlap and a line width is described by seven pixels (vertical direction in Figure 3). If no image trimming operates, then the expected line width after ink jet printing on the substrate is $\sim$300 μm. Therefore, four rows of pixels along the horizontal line (characteristic pattern) direction are canceled (trimming ratio 4 pixels/7 pixels $\sim$57%) to avoid the spreading toward the perpendicular to the line direction (the vertical direction in Fig. 3). The results can be expected to present a line width of $\sim$200 μm. With a similar procedure but in a different characteristic pattern, such as the slanted line, the trimming ratio will be different because of the inconsistency of pattern directionality and printing swath direction; in this case, five columns of pixels along the slanted line direction were canceled to get the same line width performance (Fig. 3). Moreover, some area characteristics (such as circle and square) need a higher trimming ratio compared to a line characteristic, due to two-dimensional overlap.

The trimming procedure can be effective in correcting the pattern dimension difference behavior between the original image and printed image caused by ink-substrate spreading. However, for some kinds of ink with high viscosity or a low wetting characteristic the line thickness is another important concern along with line width. Because of the low wetting characteristic, high drop overlapping will not significantly increase the line width, instead accumulating fluid to form a thicker line. Therefore, an extra procedure is needed to screen the ink amount after the trimming scheme. For example, in the application of ink jet printing of color filters for display devices, we need to accurately control the thickness at certain line widths; here we propose an image filtering method to modulate the ink overlap ratio. Thus, pattern filtering is designed to screen the overlap density along with keeping the same resolution criterion. Here, we adopted a halftoning strategy in the grouping of the individual pixels produced by the trimmed pattern. In Figures 4(a)–4(f), for example, the white block denotes trimmed data to be printed, then a halftoning space filter is operated to reduce the printing density, noted as a black block in real printing. There are many classic space filter skeletons[9] that can be applied to modulate the layer thickness. Some examples are shown in Figs. 4(a)–4(f). The key design challenge is to balance the resolution requirement and the thickness modulation capacity. Generally, if one operates a larger cluster skeleton, then thickness can be modulated more into the gray level; however, it also results in a smeared edge along the boundary and more calculation time. In Figs. 4(a)–4(f), for example, some cluster skeletons demonstrated that a fil-

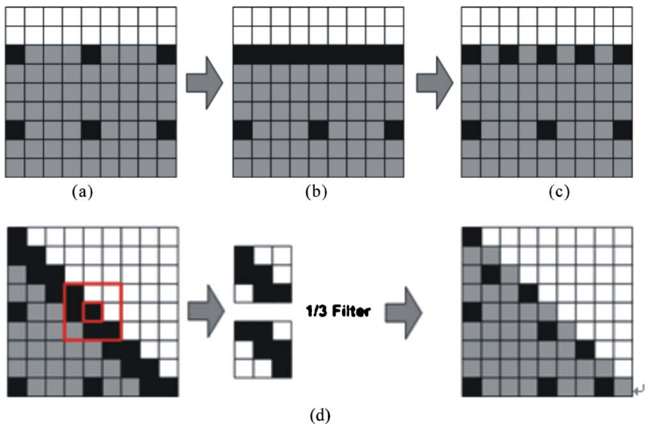

Figure 5. Example of boundary compensation: (a) Image has been processed by filtering, (b) boundary reconstruction, (c) boundary filtering, and (d) boundary filtering for slanted line.

ter ratio from 1/4 or 1/16 means that only a 1/4 or 1/16 of the drop amount is supposed to be dispensed onto the substrate and a thinner printing thickness is expected. It is noted that, even at the same filtering ratio, when a different pixel is selected, a different sharpness may result along the line boundary. In other words, the trimmed characteristic pattern should be consistent with the skeleton pixel selection in order to get better printing quality. The filter procedure is significant for modulating thickness, and a higher ratio means a lower thickness due to less deposition after filtering. The design of filtering needs careful consideration with respect to the symmetry of the skeleton to avoid the inconsistent image characteristics.

Even with trimming and filtering for controlling the line width and line thickness, the side effect is that the edge will smear because of the filtering process. Thus, to get a better line edge profile, a compensation scheme is proposed to recover the boundary sharpness after the filtering step. After filtering, a seeking scheme is applied to reconstruct the boundary and then, following a filtering description along this boundary, to fine tune its thickness presence, as indicated in Figures 5(a)–5(d). Figure 5(a) is an image both trimmed and filtered, Fig. 5(b) is the image in Fig. 5(a) with further edge reconstruction, and Fig. 5(c) is the result of the Fig. 5(b) image with a special edge filtering to keep it smooth. Figure 5(d) is an advanced scheme to deal with slanted line that depends on its local characteristics by convolution of a 3×3 matrix after operation. A boundary interlace arrangement was implemented in this case. For most of the characteristic patterns, the matrix skeleton operation is satisfactory as well.

However, those filtering schemes cannot process the arc boundary adequately for characteristics such as a circle or an ellipse. A different filtering strategy is required. Figures 6(a)–6(c) illustrates a one-dimensional $r-\theta$ filtering method, with only the rotational angle as variable. This kind of scheme is simple but not good in terms of quality, sometimes creating defects. Therefore, higher printing quality is needed for depicting the arc boundary. In Figs. 6(d)–6(f), the two-dimensional filtering process, involving calculation of an $r-\theta$ spiral path, was implemented to get a sharper line quality and its morphological characteristics. After compensation on the edge boundary, in the final step each characteristic has been identified, trimmed, filtered, and compensated, then reconstructed according to all the original characteristics to form a completed image ready to print.

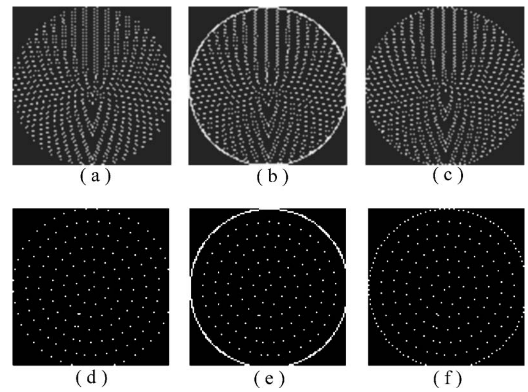

Figure 6. Schemes for circle characteristic in different methodologies: (a) only by one-dimensional filtering; (b) one-dimensional filtering, and boundary reconstruct boundary; (c) one-dimensional filtering, boundary reconstruct boundary, and boundary compensation; (d) two-dimensional filtering; (e) two-dimensional filtering and boundary reconstruct boundary; and (f) two-dimensional filtering, boundary reconstruct boundary, and boundary compensation.

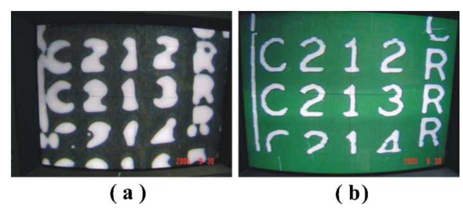

Figure 7. Comparison with and without the trimming process for ink jet printing of the legend on a printed circuit board: (a) Ink jet printing original image and (b) ink jet printing of trimmed image according to the spreading factor between the legend ink and substrate.

RESULT AND DISCUSSION

Figures 7(a) and 7(b) show the results of white legend ink printed with 600 dpi resolution for a printed circuit board. Figure 7(a) was an original image without any processing, and Fig. 7(b) was the original image with the trimming procedure as described above. Comparing these two images, it is obvious that the trimming result is clearer than the nontrimming result. In the nontrimming case ink will congregate and degrade the image. Figures 8(a)–8(f) are other examples of Yang's[11,12] ink jet printing process to fabricate a copper circuit pattern with an image trimming and filtering operation. The ink jet dispensed material is the catalyst which exchanges copper ions to form a metal pattern on the surface of the substrate by an electroless plating process. Figure 8(a) presents pixelized image data: each dot in Fig. 8(a) signifies the position to be jetted according to the original image. As mentioned before, to pursue a better printing quality, generally, we prefer to implement the trimming and, filtering, combined with boundary reconstruction to get optimal

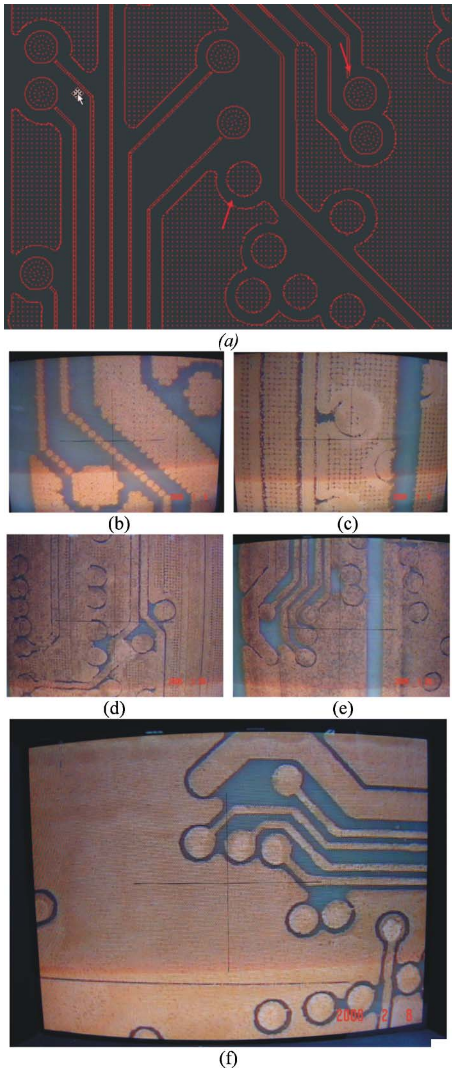

Figure 8. Versatile trimming, filtering, and boundary reconstruction results: (a) The partial demonstration of original image pattern (the red point indicates the position for ink jet printing according to resolution required), (b) original image with adoption of 1/5 space filter, (c) original image with adoption of 1/7 space filter with full boundary compensated, (d) a 1/7 space filter and a 1/2 boundary compensated filter for (a), (e) a 1/5 space filter with boundary compensated for the slanted line as in Fig. 5(d), and (f) the case (e) with further refinement by operating the circle correction step in Fig. 6(f).

line width, thickness and sharpness. Figures 8(b)–8(f) present the versatile filtering and boundary compensation, and an excellent result is shown in Fig. 8(f).

Figure 8(b) adopted a 1/5 space filter, and the edge presented a very rough printed result. Figure 8(c) changed to a 1/7 space filter with a full boundary compensation; it was found that the edge was less smooth compared to Fig. 8(b), and also found that the filter will create some discontinuities in the pattern. Figure 8(d) combined the 1/7 space filter and a 1/2 boundary compensated filter to obtain a satisfactory result at gaps between lines and pads. Figure 8(e) further evaluated a 1/5 space filter, with the boundary compensated for a slanted line as in Fig. 5(d), with almost all discontinuities smeared. Results in Fig. 8(f) were further refined by operating the circle correction step as in Fig. 6(f), where the

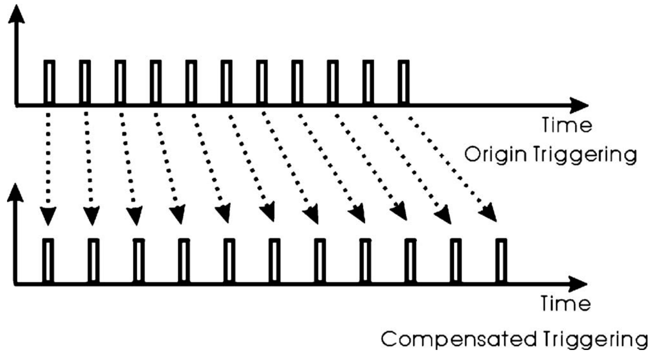

Figure 9. A conceptual compensation scheme for modulating the firing pulse according to the substrate extension from heat or stress.

line width and line gap were controlled at the desired 100 μm, as in the original input pattern.

In the above discussion, the present study successfully balanced the line width and thickness needs by a new image processing scheme; which included combining an ink-substrate surface interface as foundation for image trimming, space filtering to modulate the line thickness, and compensation along the boundary to sharpen the edge. These are implemented as in batch processes and are hard to realize in real time.

Recently, flexible substrates have become more important in the printed circuit board and display industry. The era of ink jet fabrication is coming, due to its low cost, high throughput, and the feasibility of manufacturing on flexible substrates. The innate quality of ink jet printing, with its noncontact characteristic and digitalization of patterning, makes it attractive for future manufacturing. Therefore, the key question is how to design a real-time processing scheme for ink jet printing for the roll-to-roll fabrication used for flexible electronics or flexible displays. A roll-to-roll continuous process with real-time image processing and compensating during the substrate delivery differs from "ordinary" image processing in that the logical correctness of the system requires not only correct but also timely outputs; that is, semantic validity entails not only functional correctness but also deadline satisfaction. Real-time image processing involves at least three fundamental trade-offs: performance versus image resolution, performance versus storage, and input/output bandwidth and number of tasks versus synchronization. The system needs to calculate the image variation according to the substrate delivery information and then real-time compensation of data to the print head firing system. For the roll-to-roll process, the image processing is totally different from, and more complex than, the scheme mentioned in this article. As an illustration, the image processing strategy will further need to consider the characteristic pattern extension due to the substrate delivery and thermal deterioration, rather than only the substrate spreading factor addressed issue in this article. Therefore, a real-time extra firing control by frequency timing modulation is required (as shown in Figure 9) to compensate the pattern. The challenge is how to recognize the characteristic pattern, trimming pattern, and filtering pattern within the ink jet printing firing step in real time.

This study has disclosed a novel image trimming and compensation methodology connected with the surface property to refine printing quality. Future study will investigate the real-time image trimming scheme especially for continuous roll-to-roll printing workflow, and the dynamic modulation of drop size according to pattern requirements.[13,14]

CONCLUSION

An image modifying algorithm for ink jet printing is presented in this article. It proposes a novel image trimming method for transferring the original image based on the spreading factor between the liquid-solid interface and the assumption of linear superposition for drop-to-drop overlapping. A versatile filtering function, built into the primary algorithm as a look-up table, modulates layer thickness. The scheme includes the procedures of pattern identification and locating, image separation, seamless image merging, image boundary compensation, image trimming based on the spreading factor, and image reconstruction. The filtering method included local characteristic-based boundary inspection with a defined correcting function and varied filtering patterns applied to the inner field of the boundary. The printed pattern ideally matches with the original pattern line width in consideration of wetting spread, and excellent thickness was obtained according to expectations. This development provides a powerful scheme for ink jet printing to increase the yield rate and printing quality in real fabrication. Further study will focus on the real-time calculations and develop a new scheme especially for ink jet printing in roll-to-roll fabrication.

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