Real-Time Image Compensation and Memory Arbitration for Ink-Jet Patterning on Roll-to-Roll System

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Abstract

To brew ink-jet printing (IJP) technology instead of traditional processes like spinning, screen printing, photolithography, and laser printing, used for semiconductor and display field, what is the obstacle before make mass production? The image compensation for printed thickness and resolution modulation control is the highest priority due to they dominate the device performance, especially for the roll-to-roll fabrication process. In this study, we tried to construct a novel algorithm to real-time calculate methodology to compensate the image distortion due to the thermal process and web delivery stress. Besides, this paper proposed a novel image trimming method based on the spreading factor between the liquid-solid interface and calculated image distortion, to real-time transfer the original image to a printing raster image data. In details, the trimming method included the procedure of pattern identification and locating, image separation, seamless image merge, image boundary compensation, image trimming on spreading factor, and image reconstruction, and the filtering method included the local characteristic of boundary inspection with defined correcting function and varied filtering pattern applied to inner field of boundary. To correct the landing position, this article designed new algorithm memory arbitration for the inconsistent between nozzle physical arrangement and printing data by rearranging the data format, to reduce the dispensing landing deviation.

Introduction

This article describes series of measures to straighten out printing error in roll-to-roll [1] IJP manufactures. Those measures contain compensating image data in original files and arbitrating printing data in system memory. And those printing error include deformation from thermal expansion, tension force, moisture inflation and the error of production in substrates. Through appropriate control and data processing system, the printing error can be real-time limited and reduced.

The feasibility of ink-jet fabrication is deliberated in prior works [2-4]. Ink-jet printing technology has benefits of saving material, depositing directly, economical for large panel manufacture and the applicable in flexible substrates. And the issues of roll-to-roll manufactures [1][5] are also be frequently disused in the recent. Even more, in flexible display and flexible electric circuit manufacture [6], roll-to-roll process with ink-jet printing technology is usually a reachable way to implement [7].

However, image transfer deformation and pattern shifting in flexible substrates are the primary topics in roll-to-roll manufacture. For prevent this kind of problems, prior study on compensation and memory arbitration algorithms were proposed to disclose a real-time implemented through a versatile system [8]. It consisted of a huge space data storage unit, to store image data and printing data; a printing control and print-head driving unit, to activate the printing procedure and fire the ink-drops precisely; a motion control unit, to make the action of roll-to-roll fabrication swimmingly and a central control unit, to be the user interface and be a data communicating kernel to set and manage each unit of the system.

Additionally, an image capturing unit and a high-speed computation unit must be embedded into the above-mentioned system. The image capturing unit can be used to obtain image data information of the substrate to exam the substrate distortion. And the high-speed computation unit can help us carrying real-time computation out for miscellaneous situations. Finally, a correct printing data for roll-to-roll IJP manufacture can be acquired and an accurate ink-drop deposition will be achieved simply and promptly.

Data Trimming and Dimensional Encoding

The printing resolution of a printing system should match the minimum printing spot made from one drop. In general, the printing resolution means the minimum distance of two nearby dots, so the system may print the pattern in 10μm resolution with a 100μm template. This template may change its size due to the ink wettability on the substrate. The high resolution also form high ink density of the paint, and the high ink density makes high layer thickness or ink spread out for low viscosity ink. A trimming algorithm [3][9] is brought out for resolved the problems.

The printing image should be calculated using trimming method before the Roll-to-Roll printing procedures starting. However, the substrate usually does not match the printing image due to the substrate distortion. For example, while prints pattern on printed circuit board (PCB), the printed circuit board always has expanded a little due to manufacture process. A simple method called Add-Removal method [3][9] is used to match the substrate distortion. The flexible substrate on Roll-to-Roll system should use the similar treaded method on the printing image.

The Add-Removal method is applied to the trimmed image for the flexibility on substrate variation. It just calculates the mismatch length in X and Y axis, and divides by printing resolution. The quotient is the pixel number of the original trimmed image to be added or deleted. In order to reduce the effect on discrete image, additional or diminishing rows and columns should equally put in whole image. For example, a one inch image needs to be expanded 10Mil and prepare to print at 1000DPI resolution. This image gets 1000 pixel and has to become 1010 pixel for matching the substrate size. It duplicates the 50^{th} , 150^{th} , … 950^{th} rows and inserts them behind themselves. The patterns which these rows represent may become wide but whole image expand to setting length. These discrete patterns are not so satisfying, so that another idea to solve this problem is described below.

Gerber RS274X is a description language for image pattern used widely for display and printed circuit board. It saves the information of brushes (aperture) which have defined size and sharp and saves the information of drawing straight from A to B with these brushes. Fig. 1 shows the example of Gerber aperture definition, and Fig. 2 shows the example of Gerber drawing using aperture

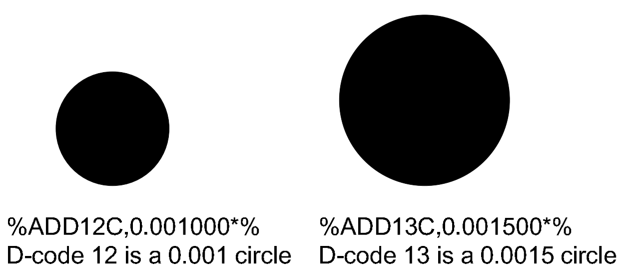

Figure 1. *Example of Gerber aperture definition*

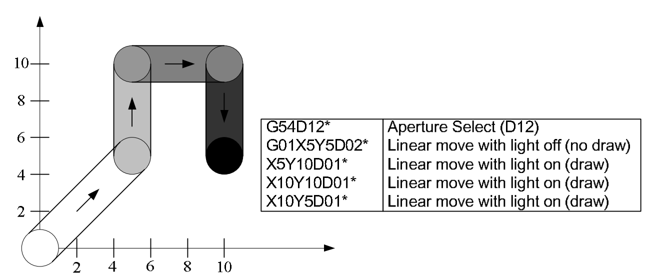

Figure 2. *Example of Gerber drawing*

Now, the prior trimming method can be exchanged to modify all of the apertures. When the apertures shrink, the lines and patterns also shrink. The old resize method can be exchanged to modify all moving distance by multiply same ratio or just change sampling resolution with same ratio. Sampling the image from Gerber file is smooth and accurate so that the distortion from Add-Removal method does not show up

.

Roll-to-Roll system needs to response to flexible substrate variation in real-time, and this new modifying method can provide fast reaction and low distortion. The realized method combines an aperture described string and a drawing described string and others parameter string. The aperture described string has a variable for trimming factor and a drawing described string has a variable for substrate variation. Any change of flexible substrate variation or environment variation can produce new image immediately.

Printing Data Compensation

After consider these measures to eliminate the effect of the above-mentioned variations of material and influences of different characteristic of ink or substrates surface. There are several issues should be concerned during Roll-to-Roll printing procedures to reduce the distortion for flexible substrate printing processes. And these distortions are usually different in each substrate during the printing procedure. In this article, the following three kinds of distortions will be discussed and settled:

1. Substrate rotation issue
2. Substrate dimensional issue
3. Substrate flatness calibration

Substrate Rotation

Before starting the printing steps, Gerber files must be transferred to image data and than the image data must be converted to a printable bit stream data format that is consisted by 1 and 0, for example, the halftone algorithm [10] can be used to obtain these bit stream data. And than these bit stream data will be stored in system memory of the printing unit. In operation, this kind of data stream can be treated as a set of stored data. Each bit can be taking into a piece of block space in memory. The following figure shows the piece data set.

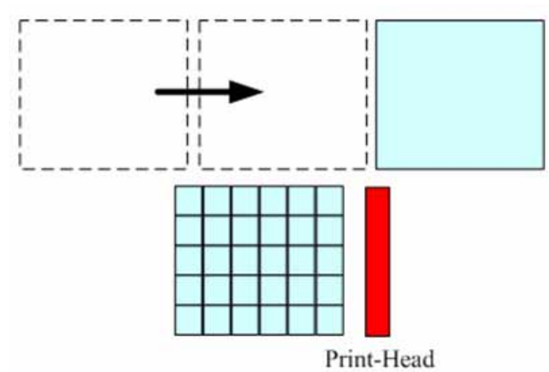

Figure 3. *Pixel data and print-head*

During the roll-to-roll printing process, inaccuracy of rotating might occur to flexible substrates. When rotating situation arisen, the printing data in the system memory must be real-time rearranged to make sure the ink-drops will be deposited to accurate positions. Fig 4 shows the rotated image bit stream data and the rotating substrate.

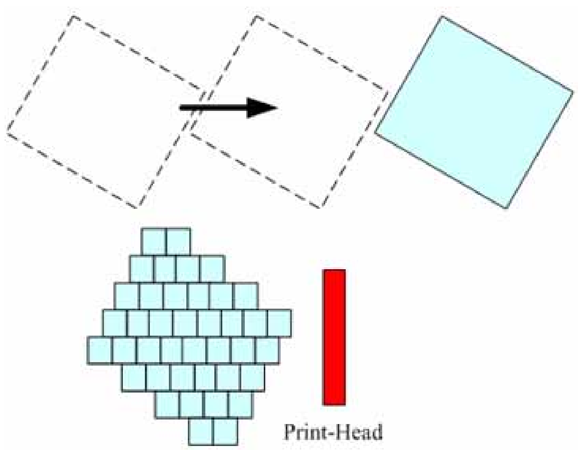

Figure 4. *Pixel data for a rotated image*

In Fig. 4, an image rotating process can be used to make printing data identical with the rotated substrate. After image data in system memory was rotated, more bits must be used to describe the printing data in the direction that is vertical to the rolling direction. In this case, a larger print-head or more print-heads must be built into the print-head module to provide a wider printable region. Fig. 5 shows an example to deal with multi-print-head printing for the rotating substrate.

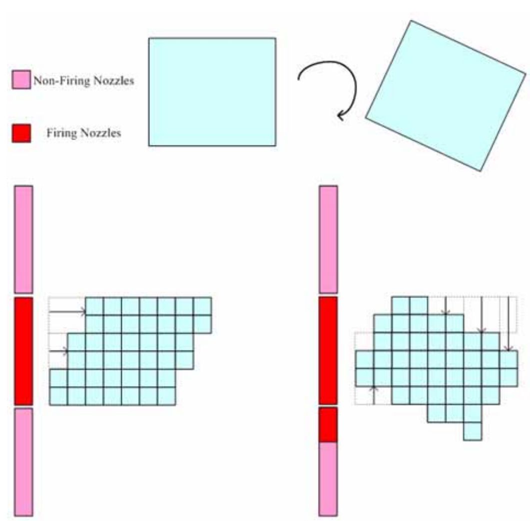

Figure 5. *Multi-print-head printing for the rotating substrate*

For rotating the bit stream data in system memory, a memory data arbitration algorithm is proposed in this article. At first, the rotating angle of the substrate must be detected by some measuring method. And the data delay count in the direction that is parallel with the rolling direction D_x can than be computed by this following formula:

$$D_x = n \times W \times \sin\theta / (PR_x)^2,\ n=0,1,2,\ldots,(L/PR_y)-1$$

,where W is the substrate width, L is the substrate length, PR_x denotes the printing resolution in the parallel direction of rolling direction, PR_y denotes the printing resolution in the vertical direction of rolling direction, θ denotes the included angle between the print-head and the substrate.

Secondary, the bit data must be shifted in the other direction that is vertical to the rolling direction. A nozzle data shift count can be used to rearrange bit data. The nozzle shift count means how many bits the firing data should be shifted to higher or lower end of nozzle arrangement.

Fig. 6 shows the geometric relationship of the rotating and original substrate. In this figure, the rotating center is o, the elevation angle of the related point r to the rotating center is ψ, the distance between the related point r and the rotating center is d, the rotating angle is θ and the shifting distance of the related point r is S. And the nozzle shift count Ns can be computed by the following formulas:

$$S = d \times [\sin(\theta+\psi) - \sin\psi]$$
$$N_s = S/PR_y$$

, where PRy denotes the printing resolution in the vertical direction of rolling direction.

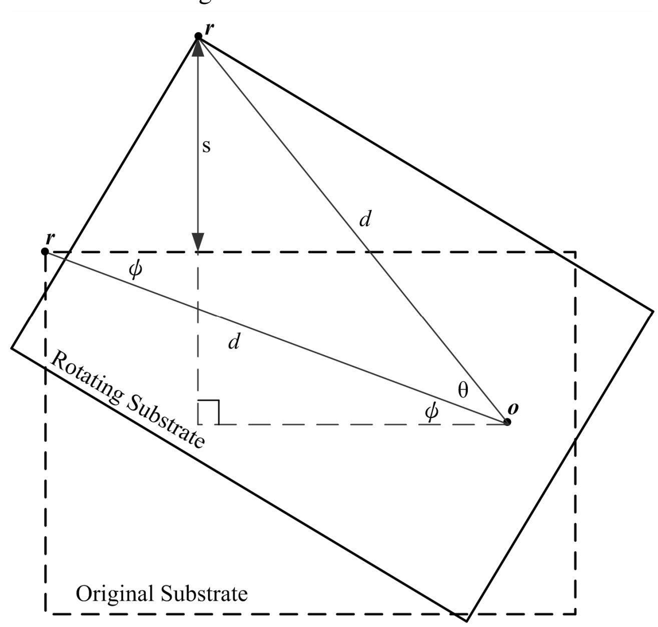

Figure 6. *Geometric and coordinate relationship of the rotating substrate compared with the original*

By real-time excusing the above-mentioned bit data delay and nozzle data shift steps, image bit stream data can be rearranged according to the rotating angle of substrate, and the ink-drops will be deposited much more precisely to the accurate positions.

Besides unitary using the memory arbitration method to arrange the printing data, a positioning exactly, moving prompt print-head module can be used to compensate the deposition error in the direction that is vertical to the rolling direction, too. In this case, only the data delay memory arbitration step should be carried out. And the nozzle shift step can be replaced by moving print-head modules to increase the data computing time and lessen the number of print-heads. Fig. 7 shows the movable print-head module and the rotating substrate. In this figure, data delay step was executed in the first step and the movable print-head moves up and down according to the rotating angle and shape of the substrate.

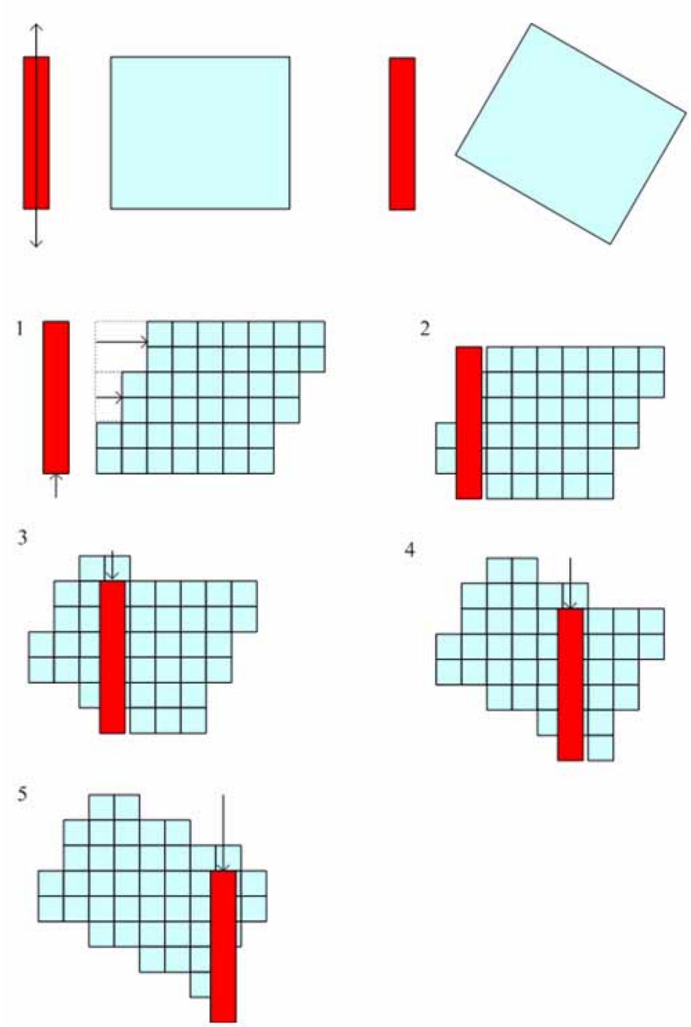

Figure 7. *The movable print-dead module and the rotating substrate.*

Substrate Dimensional Issue：

The event of expansion or shrinking might occur to substrates during the roll-to-roll printing procedural. In the case of the expansion or shrinking rates are all equal in each point of the substrate, these deformation rate can be easily computed by detecting and recognizing the position marks at four corners of the substrate. And the compensation method can than be carried out in vertical and parallel directions of the rolling way.

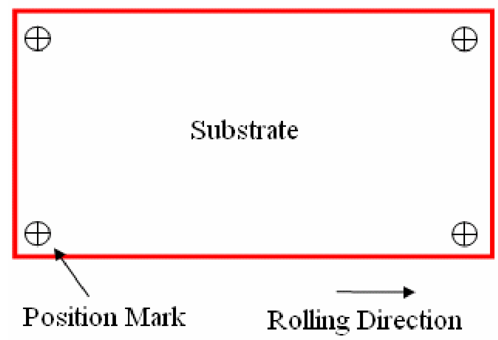

Figure 8. *Substrate with position marks at four corners*

When the substrate expanding in the direction that is vertical to the rolling direction, ink-drops should than be separated up. Contrarily, ink-drops should be gathered in when the substrate shrinking in this direction. In other words, the deformation in the vertical direction can be compensated through tuning the printing resolution in this direction. And, this demand can be reached immediately by rotating the print-head module [11].

Fig.9 shows the geometric relationship of the rotated print-head. In this figure, d is the nozzle distance of the print-head, dv and dh are the components of nozzle distance d in the vertical and horizontal directions respectively, and θ is the rotation angle of the print-head. In the case of the vertical resolution is d_v, the rotation angle can be computed by the following formula:

$$\theta = \mathrm{Inv}[\sin(d_v/d)] \quad (1)$$

, where Inv denotes the inverse trigonometric function.

From the above, the objective printing resolution PR, the objective angle θ_{obj}, the reference angle θ_{ref} and the print-head tuning angle Δθ can be formulated as:

$$\Delta\theta = \theta_{ref} - \theta_{obj} = \mathrm{Inv}[\sin(dv/d)] - \mathrm{Inv}[\sin(PR/d)] \quad (2)$$

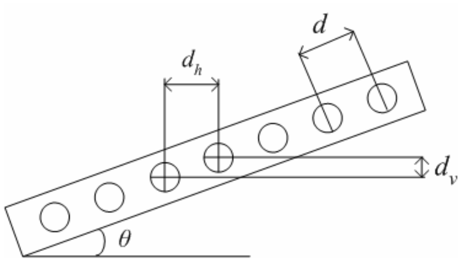

***Figure 9**. Geometric relationship of the print-head*

In the beginning of printing process, print-head modules were erected in a initial rotating angle θ_{ref} and by tuning the rotating angle $\Delta\theta$, arbitrary printing resolution in the vertical direction can be reached. However, according to the previous researches [12], a miss-matched deposition crooked line may appear during the printing process with rotated print-heads. And this crooked line usually caused from inconsistent situations between the nozzle physical arrangement and the printing data.

Fig. 10 shows this miss-matched deposition situation. In this figure, four nozzles in the print-head are simultaneous driving nozzles, and the patterning resolution PR is just equal to the vertical nozzle distance component dv. After n times of nozzle firings it will be observed that there is an oblique line with the slope of:

$$d_v/((d_v\times n)\square d_v) \quad (3)$$

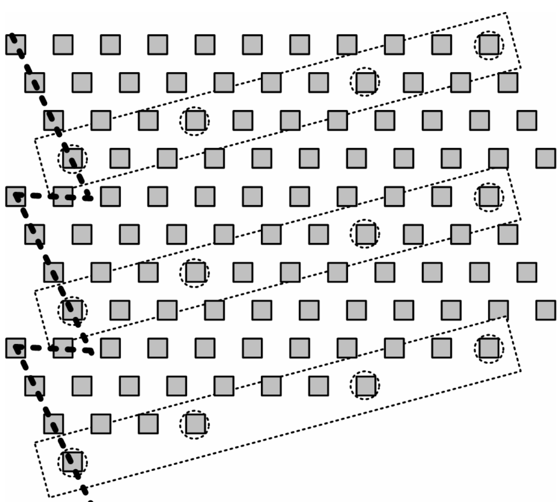

***Figure 10.** Meantime-driving nozzles and crooked lines*

Fig. 11 is the sketch diagram of the data shift arbitration. In this figure, crooked error for each row of drops are all reduced to less than a printing resolution, it means that, this error is less than one pixel. In this diagram, gray blocks mean the tuned ink-drops, and white blocks mean the original ink-drops. 1-1 denotes the first ink-drop in the first printing row, 1-2 denotes the second ink-drop in the first printing row, 2-3 denotes the third ink-drop in the second printing row, n-m denotes the mth drop in the nth print row. And every ink-drop in a printing row is fired by the same nozzle.

It can be observed from the Fig. 11, there are four ranks in the printed pattern. The first rank marked as Rank 0; where the ink-drops are deposited at the original positions that are processed through the data advance adjustment step only, without the fine tune step. Similarly, ink-drops in Rank 1 are processed through the data advance adjustment step with once fine advance tune. Ink-drops in Rank 2 are processed through the data advance adjustment step with twice fine advance tune, and so forth. And the deposition error for each row of drops are limited to –PR/2~PR/2.

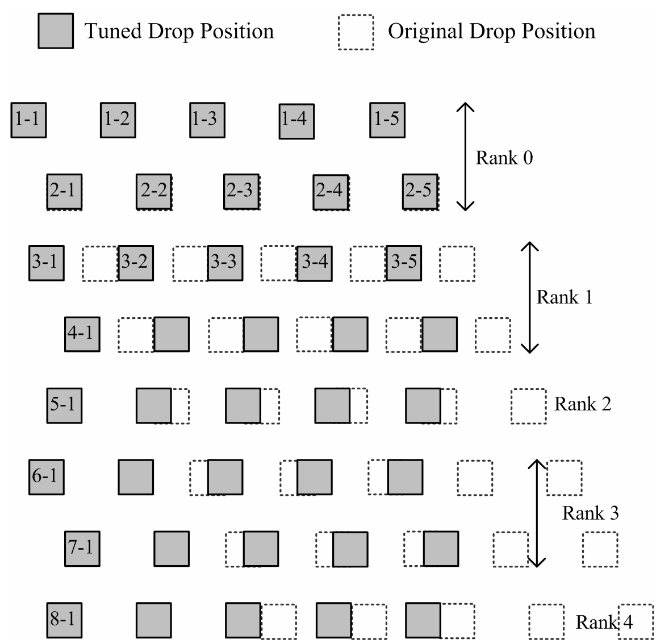

***Figure 11.** Crooked line repaired through nozzle data fine tune.*

On the other hand, when substrates deform in direction parallel to master delivery, this deformation can also be compensated through tuning the printing resolution in the parallel direction of rolling. When substrates expanding in the parallel direction, ink-drops should than be separated up (lower resolution), and ink-drops should be gathered in when substrates shrinking in (higher resolution) this direction.

Previous researches proposed the divided synchronous frequency control method [13] can be used to procure this requirement. By tuning timing of trigger pulses, firing pulses and the firing frequency can be adjusted to change the printing resolution. Fig. 12 shows the relationship between trigger pulse, firing pulse and ink-drops.

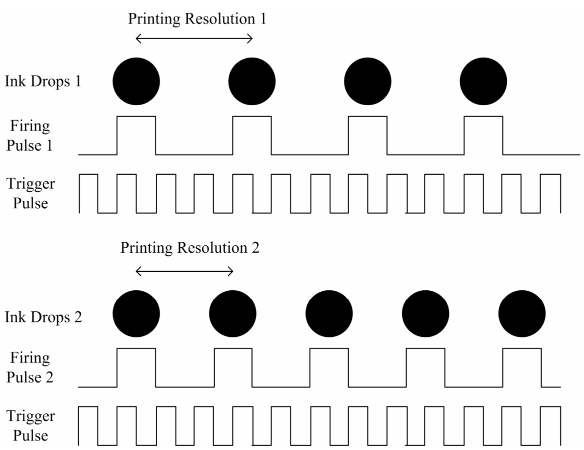

Figure 12. *Relationship between trigger & firing pulse*

Through tuning the trigger pulse, kinds of printing resolution in the parallel direction of rolling can be reached. And through rotating the print-heads, variable printing resolution in the vertical direction of rolling can also be achieved. By use of the above-mentioned methods, deformation of expanding or shrinking on substrates can be compensated and ink-drops will be deposited more accurately.

***Substrate Flatness Calibration*：**

Another deformation is the substrates curving, especially in flexible substrates. In spherical surface printing [14][15], ink-drops must be deposited according to the curving rate of substrates. In cases of large curving rates, ink-drops should be fired tighter, and ink-drops should be fired sparser for small curving rates. From the prior studies [3][8-9], the divided synchronous frequency control method has the ability to make over the constant firing frequency into a variable one. And by use of tuning firing frequency, ink-drops can also be regulated to produce a uniform landing.

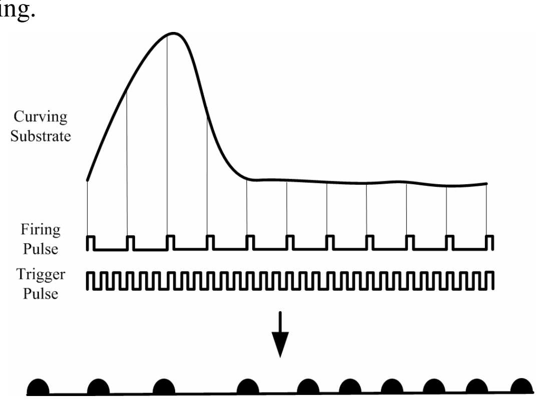

Figure 13. *Printing on curved substrate without compensation.*

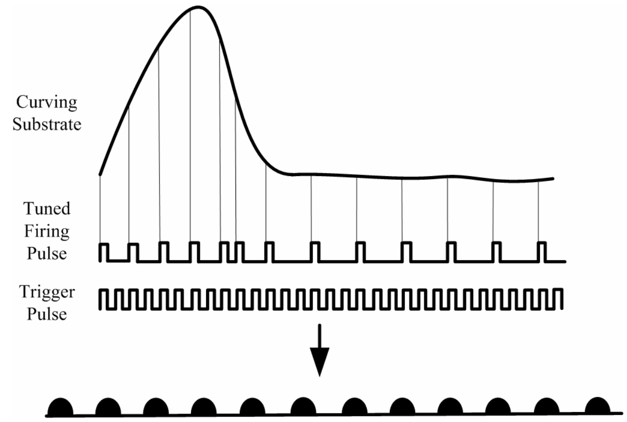

Figure 14. *Printing on curved substrate with frequency division compensation*

In use of the divided synchronous frequency control method, firing pulses are produced according to the trigger pulses. Fig. 13 shows the curving substrate printing process with a constant firing frequency and Fig. 14 shows the curving substrate printing process with a variable one. It can be observed from Fig. 13, printing with a constant firing frequency will allow non-uniform depositions in curving substrates. And by procuring printing process with variable firing frequency, landing position of ink-drops can be regulated and obtain the printed manufacture uniformly. The variable firing frequency division number can be similarity obtained through the following formula:

$$D = r - r\times\cos\theta = r\times[1-\cos\theta] = L\times[1-\cos\theta]/\ 2\times rad(\theta)$$
$$N = SG\{D/T\}$$

Where N is the variable firing frequency division number for the curving substrates, θ is the elevation angle of the rolling table to the curving point, L is the actual length of the curving substrate, D is the projection length of the curving substrate, and r is the radius of curvature. The geometric relationship diagram of the curving substrate and those parameters in this formula are shown in Fig. 15.

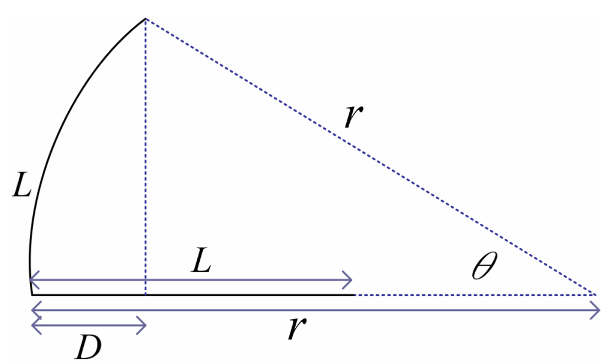

Figure 15. *Geometric relationship of the curving substrate*

Conclusion

In this article, we proposed a novel algorithm to conform image with the substrate in rolling process. It can provide fast response for making printing image data with accuracy continuous patterns. Printing data compensation considers three kinds of distortions, substrate rotating, expansion and shrinking, and curving. All of them have corresponding algorithm to correct these flexible substrates variations. Different methods can be used in different situations which include production time, printing accuracy, system mechanism, etc. Furthermore, these methods are distributed over software, firmware, and hardware. After estimating the loading of calculation and flow of process, these methods can be used on the same flexible substrates, and the patterns can be printed correctly and fast on the flexible substrates of Roll-to-Roll system.

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