Achieving High Accuracy and Precision Inkjet Drop Placement Using Imperfect Components in an Imperfect Environment

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Abstract

Drop placement accuracy and precision are the critical performance values of industrial ink jet deposition systems. Imperfect components and environments have severe impacts on drop placement. Litrex has identified over 120 error sources and developed engineering solutions to address the errors. In this paper, improved results using thermal compensation and stage mapping techniques are demonstrated. A recent progress in inkjet fabrication of multi-color electrophoretic display on flexible substrate with large distortion is also demonstrated.

1. Objectives and Background

Imperfect components are often seen in an industrial ink-jet system due to complicated system integration while environmental variation is normally unavoidable in real applications. These factors have significant impacts on final product performance. Correction and compensation techniques are thus very critical components in ink-jet product engineering. The main objectives of this work are to identify various error sources, develop engineering solutions to achieve high drop placement accuracy and precision in order to meet demanding needs of various burgeoning applications.

2. Inkjet Printer and Motion System

A typical inkjet printer for industrial applications has X-Y-Z stages, variable pitch rotation stage, and multiple motion coordinate systems depending on system complexity. **Fig.1(a)** is a CAD rendering of Litrex single print-head Gen2 printer's main system assembly. It has one main coordinate system for printing and substrate alignment as the single print head and the alignment optics are mounted on the same X-stage. In this case, variable pitch is achieved through a rotary stage onto which the single print head module is mounted. Drop analysis module and maintenance module have their own motion systems that are much less critical, and do not have direct impact on drop placement accuracy and therefore are excluded from the error source analysis.

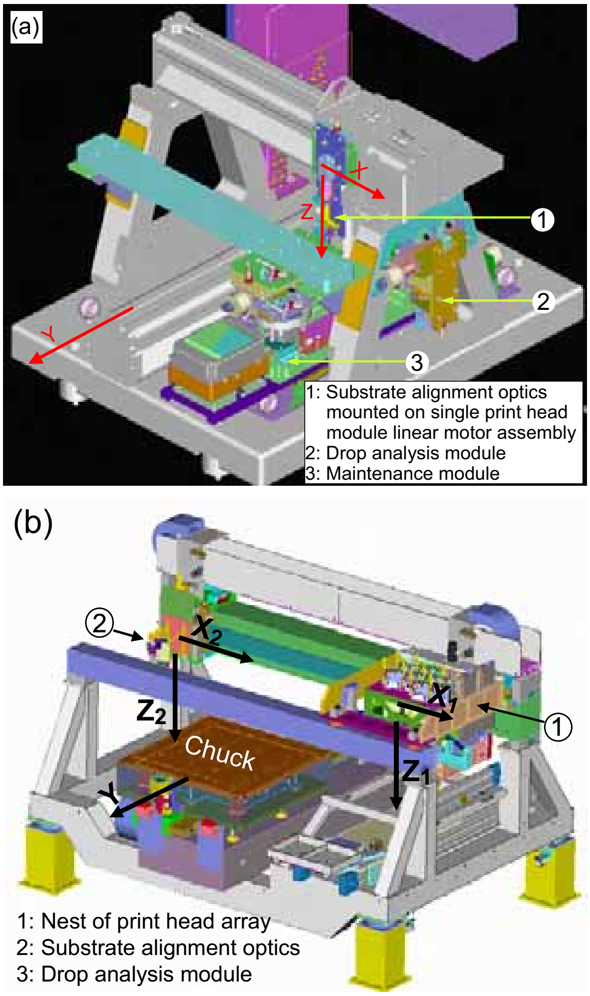

Fig. 1 CAD rendering of Litrex Inkjet System main assemblies: (a)Gen2 system (print head module, ink supply module not displayed); (b)Gen5 system (maintenance module, ink supply module not displayed).

For large platform inkjet systems, stages and motion systems can be much more complicated. As illustrated in **Fig.1(b)**, substrate alignment optics module and variable pitch array made of multiple print heads are carried by different X-Z stages. The chuck that holds the substrate via a vacuum system is carried by the Y-stage. Here, there are two coordinate systems including print coordinate system and alignment coordinate systems. The print coordinate system is X1, Y, and Z1. The alignment coordinate system is X2, Y, and Z2. Both coordinate systems share a common Y axis.

3. Sources of Error and Compensation Technology

Litrex has identified over 120 sources of error in developing multiple high-precision inkjet systems from Gen2 to Gen8 systems.

Table 1 lists a summary of error sources for a variable pitch Gen5.5 system and the error budgets after implementing various compensation techniques. Each listed source of error can be further decomposed into sub-items depending on specific system design.

An Error budgeting tool (**Fig. 2**) has been developed to identify, analyze and create budget of all the error sources. Since error sources differ in distribution, random or fixed and sometimes they are not independent, Monte Carlo simulation is implemented in adding all the errors beyond general statistical rules for processing normal distributions.

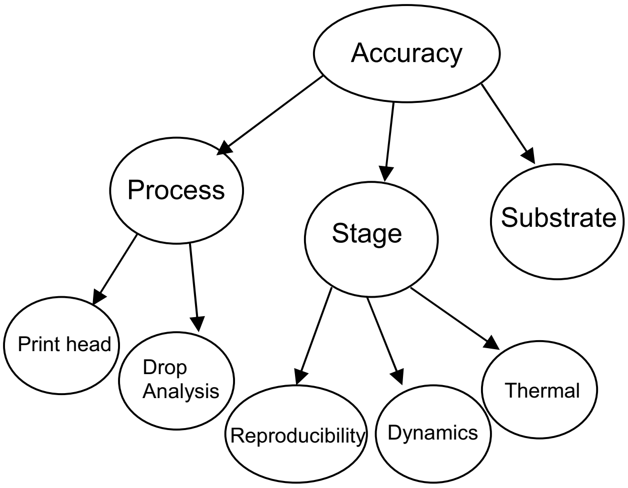

Fig.2 Diagram of Error Budgeting Tool.

Table 1 Summary of Error Sources and Error Budget for a multi-head Printer System.

System Error Source Summary	Linear Error (±µm)	
	"X" (Upper Axis)	"Y" (Lower Axis)
Stage Calibration/Mapping		
XY Stage Errors	5.1	4.8
Print Gap Error	▨	5.8
Fiducial Camera to Nozzle Offset	6.8	6.6
Drop Placement Accuracy	8.1	6.6
Substrate Accuracy		
Substrate Thermal Stability	2.7	3.2
Plate Alignment		
Fiducial Acquisition (Vision System)	0.3	0.3
Fiducial Camera Mounting Stability	1.4	1.4
Plus Static XY Stage	5.0	4.8
Print Process		
Rotary Flexure In-Position Stability	0.3	0.2
Rotary Flexure Errors	4.9	4.9
Rotary Stage Bi-Directional Repeatability	2.6	1.7
Interpolation	0.5	0.5
Total (±µm)	**7.6**	**7.6**
Total (±µm) (Monte Carlo simulation)	**10.6**	**10.7**

3.1 Stage Error Sources and Compensation

Major types of error sources in a stage include reproducibility, thermal, dynamic/control and geometric. Rail "bowing" is one of the geometric errors and normally gets worse as the stage size increases. Since manufacturing a perfect stage is practically impossible, special compensation techniques have to be applied besides specifying the stage with extremely tight tolerances for critical elements. However, reproducibility and thermal errors are very difficult to be fully compensated so that these should be at minimal in design concept consideration. Litrex has developed special stage characterization and mapping techniques to measure and correct the relevant error sources on the stage.

For Gen2 stage, a master plate with accurately positioned fiducials (±1μm position accuracy) together with a substrate alignment optics system mounted on the single print head stage are utilized to measure XY orthogonality, X-axis and Y-axis straightness and actual stage position. Based on this measurement, the total error at each position over the entire travel is calculated. Z mapping is not conducted for Gen2 stage as it is fairly easy for stage and chuck makers to meet the design specification at such size.

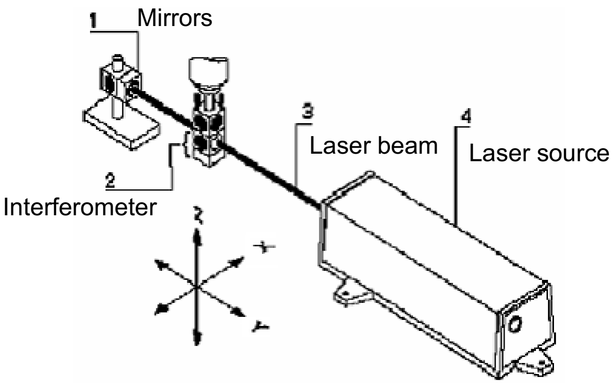

Fig. 3 A typical laser interferometer system used for stage characterization & mapping.

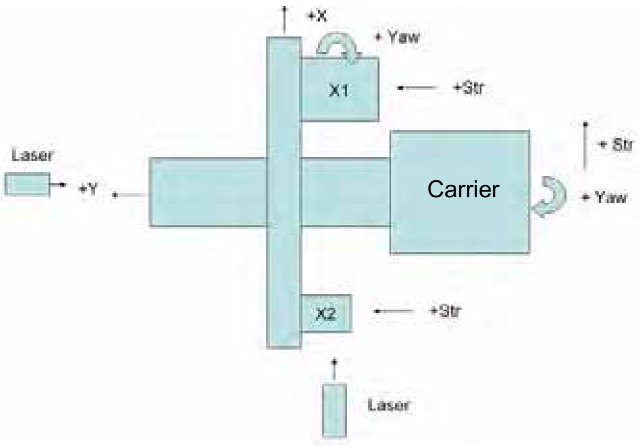

Fig. 4 Typical setting for characterizing X-Y stage motion sources of error using laser interferometer system. X1 is for nest of print head array and X2 is for substrate alignment optics.

For large platform stages which is significantly more complicated, a laser interferometer system (**Fig. 3 and Fig.4**) is used to measure errors in the XY plane and a capacitive sensor to measure Z errors. Using these measurements, the total influence of each error at the point of interest (POI) is calculated. These calculations are performed over the full travel of the stage. Each axis of motion has three linear errors and three rotational errors. The linear errors are linearity, straightness of travel, and flatness of travel. The rotational errors are pitch, yaw, and roll. These six errors will vary over the entire travel of each axis. So with five separate axes of motions, 30 different error sources that continuously vary throughout its travel needs to be corrected. Fortunately the measurement is taken at POI which can be just a simple point in some cases such as the focal point of the fiducial camera (X2), and thus all the rotation error can be ignored. In other cases when POI is not a single point, the rotation error of pitch and row are either integrated into some of the linear errors or are small enough to be ignored, the only rotation error needs to be measured is Y-Yaw and X1-Yaw.

Orthogonality correction is implemented assuming the Y axis is zero. Then the angle of the X axis is adjusted to make it 90°.

Z mapping is a bit simpler. A capacitive sensor is mounted on Z1 and Z2. Then the X and Y axis are moved over the entire surface of the chuck taking Z height measurements. These Z measurements combine all Z error sources including flatness of travel, chuck level, and chuck flatness, Y axis pitch, Y axis Roll, X1 axis pitch, X1 axis roll, X2 axis pitch, and X2 axis roll. This corrects the translation errors. However, the actual rotation errors of the planar surface can not be corrected.

After all the measurement and calculation are completed, compensation tables can be created comparing actual position of the stage relative to desired position and downloaded into controller to correct error. The desired position is simply encoder feedback. In motion control, the actual position is based on the sum of the encoder position, map correction, and offset. The offset is tiny enough so that it is ignored, and the actual motion trajectory of any move incorporates the map correction. This is done for all axes with the total correction for each axis. Through such stage characterization and mapping, the X-Y stage errors have been reduced by almost a factor of 10. In case of a recently built multi-head system with improved design, the X-Y stage errors are reduced by a factor of 12.

Fig. 5 & **Fig. 6** show accurate PEDOT ink drop placement inside sub-pixels of a typical PLED plate using a Litrex Gen2 printer.

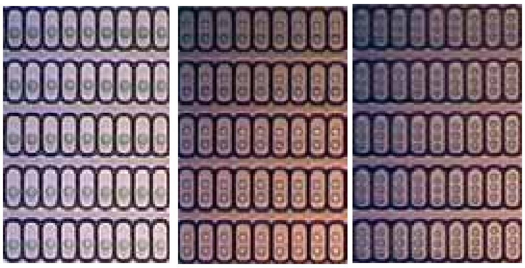

Fig. 5 PEDOT ink drop placement within sub-pixels after stage mapping implementation.

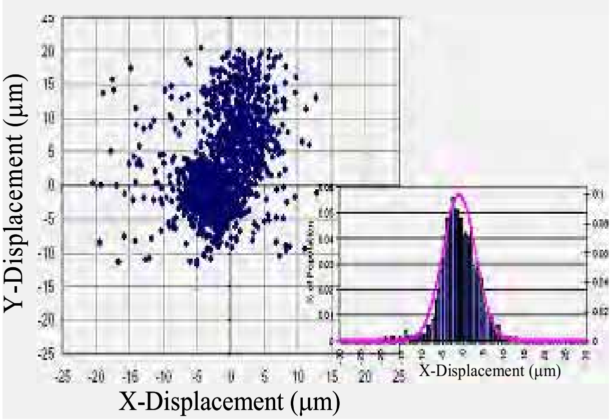

Fig. 6 Drop placement with stage mapping: stage accuracy results in drop placement of 4µm (1σ) over one week is maintained.

3.2 Print Head Related Error and Compensation

Generally, print head induced drop placement error is the largest source of error, even after various compensation techniques are implemented. In case of printer with multiple print head arrays, the largest portion of error comes from the print head arrays.

The second largest portion of the error comes from individual print head. Currently the best drop jetting directionality of commercially available print heads with polymer or metal nozzle-plates is about ±10mrad, which adds 5µm drop placement error at standard printing gap of ±0.5mm. By implementing silicon nozzle-plates precisely manufactured using MEMS process technology, the drop directionality is expected to be about ±5mrad.

In addition to the jetting directionality issue, all commercially available print heads have large nozzle-to-nozzle variation (up to ±10% or larger) in jetting velocity and volume. As illustrated in **Fig.7**, at standard printing gap of 0.5mm and nominal jetting velocity of 5m/sec, 10% deviation in drop velocity can cause 10 µm drop placement error in printing direction at 1.0 m/sec required for LCD Panel mass production. Further increase in drop velocity to ~8.0 m/sec which is close to the limit in most cases, the drop placement error can be reduced to about 7 µm. However, this amount of error is still quite significant. Litrex systems have utilized Drive-Per-Nozzle^{TM} (DPN^{TM}) technology to fine tune waveform of each individual nozzle to minimize drop velocity variation down to 2% as shown in **Fig.8**.

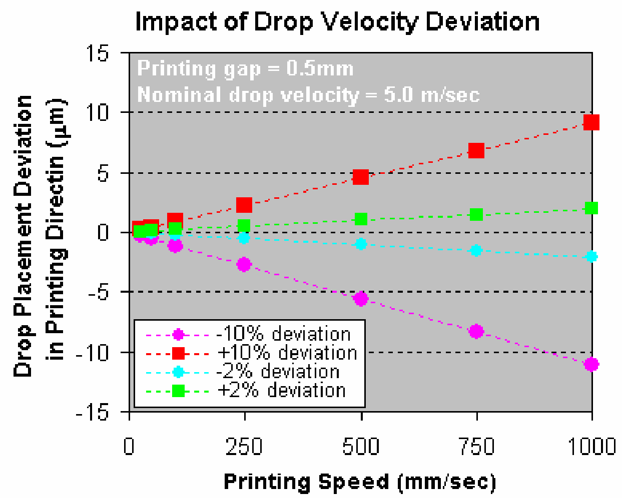

Fig.7 Impact of drop velocity deviation on drop placement accuracy in printing direction.

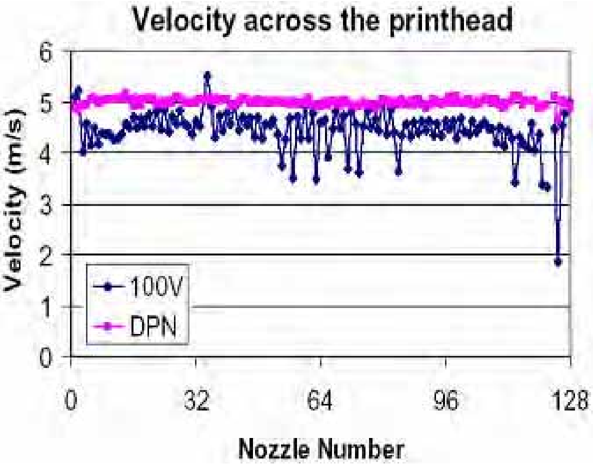

Fig.8 Drive waveform tuning for drop velocity.

Although drop placement can be improved using DPN™ technology, proper head maintenance is still very critical. Improper head maintenance can easily lead to bad drop jetting directionality, nozzles not jetting, nozzle clog, and finally shortening the head life time. **Fig. 9** is a typical example of how proper head maintenance can improve drop jetting directionality so that better drop placement accuracy and precision can be achieved. Print head maintenance has become one of the critical portions in ink jet process technology. Litrex provides various hardware and software controls for developing print head maintenance protocols towards mass production.

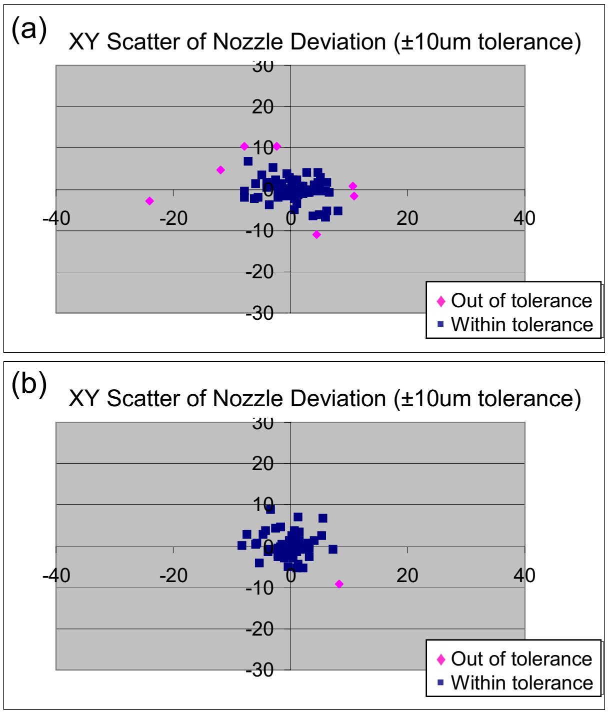

Fig. 9 Improvement of nozzle jetting directionality by proper head maintenance.

3.3 Thermal Variation and Compensation

Thermal variation is another source of large error. Very small changes in the ambient temperature can lead to large dimensional mismatches as illustrated in **Table 2**. Such effects become much more significant at larger distances as a temperature gradient gives bending which rapidly gives a larger error if the length increases. Some of the important parameters to be considered include heat conductance, thermal expansion/contraction coefficients, and temperature gradients in time & location, heat capacity of elements and location of heat sources. For large platform systems such as a Gen5 system with chuck size exceeding 2-meter square and travel distance twice that dimension along Y-axis and along X-axis roughly equal to the substrate size, impact of thermal variation can be significant. Unfortunately, only thermal expansion or contraction can be corrected by proprietary software and/or motion control compensation techniques. Non-uniform and random thermal variation is difficult to be fully compensated. Therefore, ambient temperature variation has to be controlled within ±2.0 °C which is quite standard in modern FPD fab environments. **Fig. 10** demonstrates improvement of drop placement accuracy after linear thermal compensation in printing a Gen2 size plate.

Table 2 Commonly Used Engineering Materials Thermal Expansion/Contraction Coefficients.

Materials	κ $(\times 10^{-6}/^{\circ}C)$	ΔL / °C (μm/m)
Corning EAGLE^{2000} ™	3.18	3.18
Granite	8.5	8.5
Austenitic Stainless Steels	17	17
Aluminum	23	23

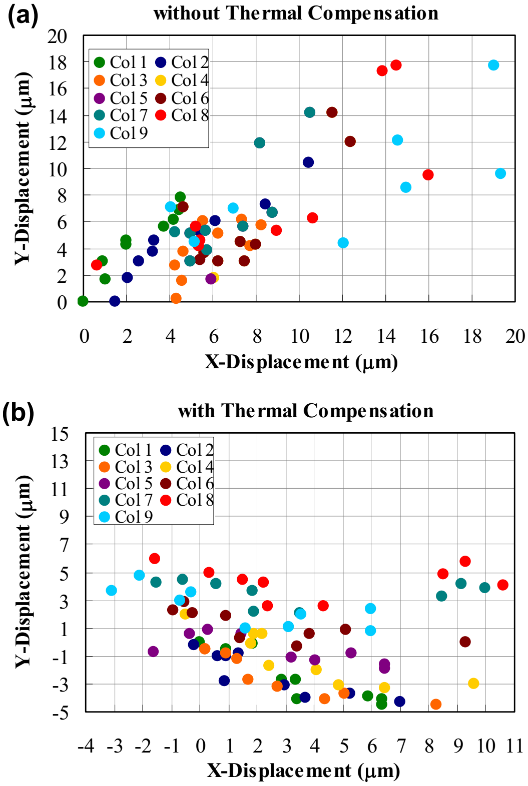

Fig. 10 Drop Placement (a) with & (b) without Thermal Compensation measured using a Mitutoyo QV404 on a plate with 9x9 displays.

3.4 Substrate Related Error & Compensation

Substrate related errors mainly come from thermal variation as mentioned above, chucking stresses & strains, pattern distortion induced by previous fabrication steps, surface condition variation and pre-treatment non-uniformity. Fortunately, some of these substrate characteristics can be compensated by properly designed inkjet printers. This is one of the key advantages of inkjet for very large substrates. Compensation is possible for errors in mask alignment, thermal induced geometric variation. Currently only linear and fixed distortion can be easily compensated, though theoretically any fixed distortion can be corrected at significant sacrifice of throughput. Litrex has developed specific software features and substrate chucking techniques to handle some of the fixed but non-uniform substrate distortions as mostly seen in flexible displays applications which normally have large tolerance on drop placement accuracy and precision. In a recent joint development work with SiPix Imaging Corporation in fabricating multi-color electrophoretic display (EPD), the black-matrix pattern on flexible substrate has angular (~0.8^{o}) and linear distortion (~0.2%) with certain amount of center-to-edge non-uniformity introduced in the pattern fabrication step by roll-to-roll hot embossing process. In this case, just the amount of angular distortion could lead to drop misplacement by about one sub-pixel in X-direction for printing very seventy sub-pixels in Y-direction. Special techniques are therefore developed to successfully achieve multi-color printing without color mixture (**Fig.11**).

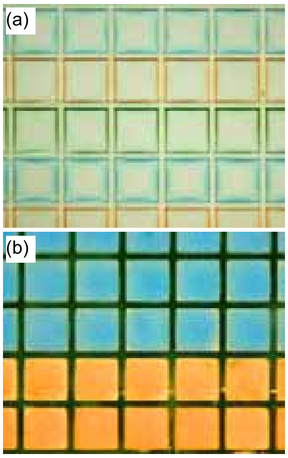

Fig.11 Microscopic images of multi-color inkjet printing on flexible substrate with clean color separation: (a) as-printed RGB pixels; (b) sealed EPD film.

4. Conclusions

With identified error sources and thus developed compensation techniques, Litrex has been able to deliver products to meet various application needs, and is stepping forward towards larger platform systems for more demanding LCD panel mass production. A Gen2 printer with very high drop placement accuracy of ±5μm and a Gen4 printer with target drop placement accuracy of ±10um are under development for high resolution display applications.

5. Acknowledgements

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